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HYDRAULIC MODEL STUDIES OF THE MODIFIED OUTLET WORKS STILLING BASIN NAVAJO DAM COLORADO RIVER STORAGE PROJECT NEW MEXICO

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ABSTRACT

Damage which occurred to the hollow-jet valve outlet works stilling basin at the Navajo Dam was duplicated in a 1:12 scale model. Severe abrasion damage in the upstream portion of the prototype basin probably occurred during several months' operation at approximately 30% valve opening under 245 ft of head. Abrasion in the downstream end probably occurred during operation with 100% valve opening and about 280 ft of head. Model tests indicated the original hollow-jet valve basin, with converging wedges and a center dividing wall, could not be improved in efficiency of energy dissipation and stability. This design, however, permitted the development of areas of intense turbulence, with accompanying circulation of abrasive materials. Also, the center wall was subjected to fluctuating pressures which could result in structural damage due to vibration. The basin was modified by eliminating the center wall and wedges, reducing the allowable maximum discharge, and paving part of the downstream channel. The paving is necessary to prevent streambed material from entering the modified stilling basin. Tests on the original configuration under various operating conditions, on 7 proposed modifications, and on the recommended design are described. An appendix reviews damages reported in other similar stilling basins.

DESCRIPTORS-- research and development/ *outlet works/ *model tests/ water pressures/ hydraulic models/ piezometers/ pressure measuring equip/ energy dissipation/ riprap/ velocity distribution/ hydraulic jumps/ hydraulics/ hydraulic structures/ erosion/ high pressure valves/ hollow jet valves/ *stilling basins/ rigid linings/ wave action/ vortices/ *damages/ abrasion/ scour/ concrete structures
IDENTIFIERS-- Navajo Dam, N Mex/ New Mexico/ Colorado River Storage Proj/ design modifications

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PURPOSE

These studies were conducted to investigate the causes of damage to the existing prototype stilling basin and to determine necessary modifications to the basin to insure against continued damage during future operation.

CONCLUSIONS

1. The model confirmed that damage to the prototype stilling basin was caused by circulation of abrasive material which moved into the basin from the downstream channel. The severe damage in the upstream portion of the basin probably occurred at a discharge of approximately 1,840 cfs (cubic feet per second) with reservoir elevation 5965 (about 245 feet of head on the valves). Both valves were about 30 percent open. Damage to the downstream portion of the horizontal basin floor probably occurred with both valves 100 percent open at approximate reservoir elevation 6000. Discharge was about 3,940 cfs.

2. The original design of the stilling basin, with converging wedges and center dividing wall, could not be improved upon with respect to efficiency in energy dissipation and stability of turbulent action in the basin. However, the high efficiency of the basin resulted in areas of intense turbulence which made the basin more susceptible to damage by the circulation of abrasive materials. The studies also indicated that at a discharge of 3,940 cfs, the frequency of pressure fluctuations matched the natural frequency of the prototype wall. Resonance of the wall would result in moments at the base of the wall several times greater than those used in the design.

3. The model showed that the prototype outlet works could be operated at a discharge of 1,000 cfs for reservoir elevations below approximately 6000 without causing additional damage to the stilling basin. Periodic inspections by divers during operation under these conditions supported this finding.

4. Several modifications to the original design were tested to develop a stilling basin which would allow sustained operation of the outlet works without additional damage to the basin. The converging wedges were removed to eliminate confined areas of intense turbulence. A 2-1/2:1 chute was installed at the upstream end of the basin to induce lateral spreading of the jets in order to maintain a high bottom velocity and sweep material from the basin floor. The center wall was removed with the stipulation that the outlet works should not be operated with only one valve open. A 12-inch layer of concrete was added to the inner surfaces of the outside walls and basin floor to repair the damaged areas and provide additional strength.

5. The model showed that abrasion damage could occur in the modified basin, even though this tendency was reduced. Also, the possibility remained that channel material might enter the basin during low discharges. Therefore, the downstream channel was paved for a distance of about 140 feet and a rock trap was provided between the paved area and the stilling basin.

6. The maximum outlet works discharge was reduced to 3,200 cfs. Discharges above this amount caused the stilling action to extend beyond the end of the basin with resulting large waves in the downstream channel. The 3,200-cfs discharge, in combination with operation of the auxiliary outlet works and the 30-inch bypass valve, will provide the required outlet capacity.

7. Balanced operation of both valves is necessary for satisfactory stilling basin flow conditions because of the absence of a center dividing wall. If an emergency requires operation of one valve alone, strong surging and rapid upstream flow in the nonoperating side can be expected.

8. The Navajo outlet works stilling basin problem was an individual case and the modifications developed herein apply only to that problem. The hollow-jet valve stilling basin is a relatively short basin whose high efficiency as an energy dissipator depends on the turbulent eddies within the basin. If loose material reaches these eddies, severe erosive damage to the basin will occur. These studies confirmed that the standard hollow-jet valve stilling basin will operate satisfactorily if adequate precautions are taken to keep the basin free of foreign material. Also, evidence now exists that the center wall must be designed to withstand dynamic loading.

ACKNOWLEDGMENTS

These studies were accomplished in close cooperation with personnel of the Spillways and Outlet Works Section of the Dams Branch, Division of Design. The Technical Engineering Analysis Branch performed vibration computations. Personnel of the Durango Projects Office in Durango, Colorado, and at Navajo Dam supplied pertinent data and photographs to assist important model-prototype comparisons. Mr. Donald J. Hebert from the Region 2 Office in Sacramento, California, assisted in defining the problem and formulating a testing program while on special assignment to the Denver Office. Model photography was by W. M. Batts, Office Services Branch.

INTRODUCTION

Navajo Dam is located on the San Juan River about 39 miles east of Farmington in northwestern New Mexico, Figure 1. The dam, which is a feature of the Colorado River Storage Project, is an earthfill structure approximately 3,650 feet long at the crest and 388 feet high above the riverbed. The hydraulic features consist of an uncontrolled overflow spillway in the right abutment of the dam, an auxiliary outlet works which passes under the spillway and discharges into the spillway stilling basin, an outlet works controlled by two 72-inch hollow-jet valves, and a bypass from the outlet works conduit which is controlled by a 30-inch hollow-jet valve and discharges through the spillway basin left wall into the spillway basin, Figures 2, 3, and 4.

Although the outlet works stilling basin, Figure 5, was designed according to the guidelines for hollow-jet valve basins presented in Engineering Monograph No. 25, 1/ the stilling basin departed from the standard design because it also served as a stilling basin for diversion flows during construction of the dam. The recommended basin was 8 feet longer, 0.29 feet wider, and 3 feet deeper than required according to Engineering Monograph No. 25. The 6:1 sloping concrete apron downstream from the dentated end sill was included to provide a transition from the horizontal floor of the stilling basin to the riprapped river channel. Details of the design were developed through the use of a 1:24 scale hydraulic model in 1957 and 1958. 2/ Specific attention in the earlier tests was given to the excessive basin depth and length but the model indicated that operation would be satisfactory at the outlet works design discharge of 4,580 cfs through both valves at the maximum reservoir elevation 6101.6. Model tests of other hollow-jet valve stilling basins had demonstrated the

1/ "Hydraulic Design of Stilling Basins and Energy Dissipators," by A. J. Peterka, Engineering Monograph No. 25, Revised Edition 1964.
2/ "Hydraulic Model Studies of Navajo Dam Diversion and Outlet Works Structure," by G. L. Beichley, Report No. Hyd-457, August 15, 1960.

acceptability of the design; therefore, most of the study was concerned with development of the diversion basin and a comparatively short time was devoted to study of the outlet works basin. At that time, there was no evidence that large amounts of abrasive material might enter the basin. Also, the presence of hydrodynamic forces which might cause vibration and accompanying structural damage to the center wall was not foreseen.

The operational history of the prototype outlet works is shown in Figure 6. The outlet works was operated for the first time in July 1963. Operation was almost entirely with one valve about 10 to 20 percent open until January 1964. The reservoir varied between elevations 5930 and 5940 during this time. (The centerline elevation on the upstream side of the valves is about 5720.) With this small gate opening the jet probably did not penetrate the pool and no abrasion damage occurred, although sand and gravel might have moved into the basin from the downstream channel during this period.

The outlet works was shut down in January 1964 and remained closed until May 1, 1964, when one valve was opened to 17 percent. This operation continued to May 22, and the reservoir rose from elevation 5939 to elevation 5952 (219 to 232 feet of total head). Probably no jet penetration of the pool occurred for this operation.

Between May 23 and June 10, both valves were operated at equal openings up to 25 percent. The reservoir rose from elevation 5952 to elevation 5965 (245 feet of head). Some jet penetration probably occurred. Operation then began with gate openings between 30 and 40 percent and continued until August 3, 1964. The reservoir dropped from elevation 5965 to elevation 5947 (227 feet of head) in this period. The model studies subsequently showed that this operation resulted in very strong turbulence in the upstream portion of the basin and violent vortices along the downstream faces of the converging wedges. Gravel placed in the model basin circulated violently in the upstream portion of the basin.

The outlet works continued to operate at gate openings between 8 and 35 percent until August 16. On August 21-24, engineers R. B. Dexter and C. E. Brockway, from the Hydraulics Branch, conducted tests to calibrate the hollow-jet valves. During these tests golf-ball-size gravel was observed circulating in the turbulence and was at times thrown above the water surface. Also, some abrasion damage was noted on the walls near the waterline. The appearance of small gravel near the surface indicated the possible presence of larger material on the floor of the basin.

The valve openings were limited to less than 10 percent into December of 1964, and the reservoir dropped from elevation 5953 to elevation 5944 (233 to 224 feet). The valve openings were increased through the latter part of December and the early part of January to a maximum of about 35 percent on January 14, 1965. Symmetrical operation at 35 percent valve openings continued to February 1, 1965, when the outlet works was shut down. The reservoir dropped from elevation 5940 (220 feet) to elevation 5915 (195 feet) during operation at 35 percent valve openings. The outlet works was operated for a few hours at 21 percent valve opening on April 16 and for less than an hour on April 22 and 23. On April 25 the basin was inspected by divers and soundings for the first time.

Severe erosion up to 5 feet deep was disclosed in the floor and through two layers of reinforcement steel in the walls. Reinforcing bars were exposed, broken, and bent. A cofferdam was built downstream from the basin, the basin was unwatered, and a complete inspection was made on May 3, 1965. The damage shown in Figure 7 was described in the Travel Report of the Head, Spillways and Outlet Works Section:

> "The damage was even more extensive than reported by the divers with erosion exposing reinforcement over half the height of the center wall. Erosion had extended through the top layer of reinforcement at the 30° slopes just downstream of the hollow-jet valves and loose cobbles were trapped behind the reinforcement at the upper end of these slopes. These cobbles were deposited by the turbulent flows in the basin and indicate that gravel and cobbles in the basin caused the extensive erosion damage.
>
> "The most severe damage occurred in the left side of the basin at the upstream end of the floor and center wall. Two layers of No. 11 bars at 6-inch spacing in the wall were broken and bent downstream along with No. 9 and No. 8 bars at 6-inch spacing in the top of the floor slab. The horizontal floor bars at the base of the wall had loosened sufficiently to allow flow of water from one side of the wall to the other. On the right side of the center wall the No. 11 bars were exposed and loosened but not removed. It appeared that many of the bars could be salvaged by bending back into position. Some new bars need to be spliced and welded to the existing bars. About 70 cubic yards of new concrete will be needed to replace the eroded concrete in the floor and walls upstream from the downstream end of the center wall. A few bars were exposed in the dentated sill and should be repaired.
>
> "The area just downstream of the basin was riprapped with rounded boulders, cobbles, and gravel rather than angular rock. A comparison of the construction photographs with the unwatered basin indicated considerable movement in the

riprap with a small slide on the right side near the downstream corner of the concrete basin. It also appeared that small rock and gravel had been removed from the larger boulders. These two sources account for the material that was found in the basin and caused the severe erosion."

Temporary repairs were made to the stilling basin in May of 1965. The original basin outline was restored by bonding new concrete to the damaged areas with epoxy. Intermittent outlet works operation was resumed on May 24 and continued until June 3 at valve openings between 16 and 75 percent; the reservoir varied from elevation 5975 (255 feet) to elevation 5980 (260 feet) during this period. On June 3, the valve openings were increased to 100 percent and the outlet works operated intermittently, usually 100 percent open, through July 10, 1965 (see Figure 6). The longest period of sustained operation at 100 percent valve opening was 5 days. The reservoir rose to elevation 6002 (282 feet of head) between June 3 and July 10. Figure 8 shows representative flow conditions during this period.

On July 3 a diver examination of the main outlet stilling basin revealed extensive erosion in the downstream end of the basin from the end of the center wall to the dentated sill.

Reinforcement bars were bent across the basin and two large rocks were found wedged in the dentates. The divers removed about 10 gallons of material up to 8 inches in diameter. Some scattered debris in the area of the bent up bars could not be removed.

Erosion was observed to a maximum depth of 1.2 feet at a point 25 feet downstream from the center wall and 5 feet from the outside wall. An area about 20 feet long and 20 feet wide was eroded from 0.75 foot to 1.2 feet deep in a floor slab thickness of 4 feet. The upper end of the right chute was eroded about 3 inches and reinforcement in a small area was exposed.

On July 10, another diver examination of the stilling basin was made. The report described grooves which had developed along the bottom on both sides of the center wall. The grooves were estimated to be 3 inches deep and 2 inches high extending from the upper end of the horizontal floor to the downstream end of the wall. The downstream end of the wall was undercut 2 to 3 feet and some of the draintile had been removed. The contraction joint in the center wall had opened up one-half inch at the top and a vertical crack had started 6 inches upstream of the joint. (Subsequent inspection showed that the center wall damage was not as extensive as the diver examination indicated.)

Further operation of the outlet works was suspended and it was decided to determine necessary permanent repairs to the stilling basin, with the aid of a hydraulic model.

The damage which occurred at Navajo Dam and at other locations revealed the need for some basic investigations in the movement of abrasive material in hollow-jet valve stilling basins and the distribution and analysis of hydrodynamic forces occurring on various parts of the structures, particularly the center dividing walls. Studies of a 1:12 scale model of the Navajo outlet works stilling basin were undertaken to determine necessary modifications to the original design and to gain insight into the operation of stilling basins of this type.

TEST FACILITIES AND EQUIPMENT

The 1:12 model included a short section of circular conduit upstream from the hollow-jet valves, the valves, the chute and stilling basin, and approximately 150 feet of the downstream channel, Figure 9. Water was supplied to the model by a centrifugal pump; discharges were measured with permanently installed Venturi meters. Pressure heads on the valves were measured at pressure taps located one-valve diameter upstream from the valves. The pressure taps were connected to open-tube mercury manometers. Instantaneous dynamic pressures were measured throughout the structure with pressure transducers connected to a Sanborn direct-writing recorder. Velocities at the downstream end of the stilling basin were measured with a miniature propeller meter and accompanying electronic counter. Tailwater elevations were determined with a hook gage in a stilling well and the appropriate tailwater level from Figure 10 was controlled by a tilting gate at the downstream end of the model. Discharges were set according to data from inplace calibration of the prototype valves.

The original model configuration duplicated the existing prototype stilling basin. The downstream channel was formed in sand to allow observation of the scour pattern produced by various outlet works discharges and tailwater elevations. Modifications to the original configuration are explained in the following section.

THE INVESTIGATION

Tests on the Original Configuration

Tests performed on the original stilling basin configuration were primarily concerned with attempts to duplicate significant prototype discharges, particularly those which were believed to have caused damage.

Both valves 8 percent open, Q = 500 cfs, reservoir elevation 5950 (H = 230 feet).--The prototype outlet works operated for approximately 4 months between 5 and 10 percent valve opening with the reservoir near elevation 5950. To represent this condition, the model was operated with both valves 8 percent open, with a discharge of 500 cfs. Two tailwater elevations were tested. At normal tailwater elevation 5713.7, the jets did not penetrate into the pool but rose immediately to the surface, resulting in an undulating water surface in the stilling basin and very weak wave action in the downstream channel. When the tailwater elevation was lowered to 5711.0 flow conditions were essentially identical to those just described. It was concluded that this operation was not capable of damaging the structure.

Both valves 17 percent open, Q = 960 cfs, reservoir elevation 5945 (H = 225 feet).--The prototype outlet works had operated with this combination of head and valve opening for about 2 weeks. At tailwater elevation 5719.0, the jets only slightly penetrated the pool and a high boil prevailed near the point where the jet entered the pool. Disturbance of the basin water surface was less than that with an 8 percent valve opening. Lightweight aggregate placed in the basin moved upstream between the wedges; normal density aggregate remained stationary on the basin floor.

With a normal tailwater elevation of 5714.0, the jets penetrated to just below the tops of the converging wedges. A high boil rose immediately above the downstream end of the wedges and there was slightly more surface disturbance than for tailwater elevation 5719.0. Wave action in the downstream channel was minor. Movement of aggregate in the basin was as described in the preceding paragraph.

At tailwater elevation 5711.0, the jets penetrated approximately two-thirds of the pool depth. The high boil formed 10 to 15 feet downstream from the downstream end of the wedges. Water surface roughness was similar to that described above and wave action in the downstream channel was again minor. Normal aggregate remained stationary on the basin floor. Lightweight aggregate moved upstream between the wedges and was suspended and circulated in the turbulence.

Minor abrasion might have occurred in the prototype stilling basin during this operation due to circulation of sand. The relatively short period of operation, however, probably did not result in any significant damage.

Both valves 32 percent open, Q = 1,840 cfs, reservoir elevation 5965 (H = 245 feet). --The prototype outlet works operated under these approximate conditions for a period of nearly 2 months. The reservoir dropped from elevation 5966 to elevation 5947 during this time. Three tailwater conditions were tested in the model. At tailwater elevation 5718.5 most of the turbulence was confined to the upstream portion of the basin and aggregate circulated in the turbulence. Normal density material moved along the chute and lightweight material was suspended in the flow. Weak vortices formed along the downstream face of the wedge next to the plexiglas window and it was assumed that similar vortices formed on the wedge next to the center wall. A high surface boil formed 10 to 15 feet downstream from the end of the wedges. Some splashing above the outside walls of the basin was noted and moderate wave action occurred in the downstream channel.

At tailwater elevation 5714.4, Figure 11, most of the turbulence, as evidenced by the movement of entrained air, occurred along the center wall. Sand and lightweight aggregate were suspended in the flow and normal aggregate circulated on the basin floor. Weak vortices were again noted along the downstream face of the outside wedge and, in general, the flow along the face was upward. The surface boil occurred along the center wall for a length of about 25 feet, beginning at the end of the wedges. High splashes or plumes, which represented a height of about 15 to 20 feet in the prototype, were noted. Infrequent splashing over the outside basin walls and moderate wave action in the downstream channel were observed.

At tailwater elevation 5711.0, the model end sill controlled the depth of water in the stilling basin. The turbulence occurred along the center wall to within about 20 feet of the downstream end of the wall. Material circulated on the floor and sand and lightweight aggregate were suspended in the flow. Weak vortices formed on the downstream face of the outside wedge and there was frequent downward flow along the upper portion of the face. The surface boil formed along the center wall and 15- to 20-foot-high plumes were again noted. There was very infrequent splashing over the outside walls and moderate wave action occurred in the downstream channel.

The tests described above gave sufficient indication of possible damaging conditions to warrant a more carefully controlled test of the circulation of abrasive material and resultant damage.

Enamel paint was applied to the stilling basin walls and floor, including the chute, wedges, and center wall as shown in Figure 9. The paint dried to a hard finish which chipped when subjected to the impact of gravel circulating in the turbulence of the stilling basin. Material placed in the basin ranged in size from pea gravel to 3-inch rounded rock, Figure 12A. The model was operated for 4 hours (about 14 hours prototype time) at a discharge of 1,840 cfs, both valves 32 percent open, reservoir elevation 5965, tailwater elevation 5714.4. Sand, apparently drawn into the basin from the downstream channel, was observed circulating on the top surface of the wedges. During the test the movement of the gravel in the stilling basin was audible.

Heavy abrasion damage occurred on the downstream face of the right inside wedge and on the right side of the center wall, Figure 13. Less damage occurred on the left side of the center wall. Heaviest floor damage occurred in the left bay. There was no apparent damage to the dentated end sill; however, slight erosion occurred on the floor about 15 feet upstream from the end sill. A slightly higher jet velocity or lower tailwater might have resulted in damage farther downstream. Most of the material, including a large amount of sand, Figure 12B, was found deposited in the left bay and a sandbar was formed around the downstream end of the center wall, Figure 13. Small piles of sand were deposited immediately upstream of the individual dentils of the dentated end sill.

Damage to the model stilling basin was very similar to that which occurred in the prototype basin, with the exception that the right bay was most heavily damaged in the model while the left bay was most heavily damaged in the prototype. Also, the largest amount of material deposited in the model basin was in the bay opposite to that in which the heaviest damage occurred. The material apparently circulated in the right bay, then moved to the left bay where it circulated for a relatively short period of time before the model was shut down. A similar situation probably existed in the prototype.

Deep erosion occurred in the sand channel immediately downstream from the stilling basin, Figure 11, which indicated high bottom velocities at the stilling basin exit. The upward slope of the downstream channel bottom probably also had some effect on the erosion pattern.

<u>Both valves 100 percent open, Q = 3,940 cfs, reservoir elevation 6000 (H = 280 feet).</u>--The prototype outlet works operated intermittently with these approximate conditions for about 30 days during June and July of 1965, after temporary repairs to the stilling basin were made in the spring of 1965.

Three tailwater conditions were tested in the model. At tailwater elevation 5721.5, the position of the toe of the hydraulic jump fluctuated on the chute, with the high point near the bottom of the valves. Turbulence occupied the full length of the basin to the dentated end sill. The surface boil occurred primarily along the center wall and there was frequent splashing over the outside walls. Plumes as high as 10 to 15 feet were noted.

Moderate wave action occurred in the downstream channel. Gravel placed in the basin circulated on the floor near the downstream end of the center wall. Moderately strong vortices were noted along the downstream face of the right outside wedge.

At tailwater elevation 5715.3, the top of the center wall was exposed to view and the jump profile was relatively steep, Figure 14. The jets turned upward from the floor at a point 20 to 30 feet downstream from the end of the center wall. Surface turbulence and foam extended beyond the basin into the downstream channel. Material circulated very rapidly on the basin floor between the end of the center wall and the dentated end sill. Moderate vortex action occurred on the right outside wedge and flow was generally downward along the downstream face of the wedge. Moderate to strong wave action existed in the downstream channel.

At tailwater elevation 5712.5, the upper 6 to 8 feet of the center wall was exposed and the jump profile was very steep. The jets remained on the basin floor beyond the viewing window, probably to the dentated end sill. Circulating material was not visible but could be heard downstream from the viewing window. Surface turbulence extended into the downstream channel and strong wave action existed. Vortices formed along the downstream face of the right outside wedge and flow was downward along the face.

Enamel paint was reapplied to the stilling basin and material ranging in size from pea gravel to a maximum size of about one-half inch was placed in the basin. Lightweight aggregate of pea gravel size was also included. Larger sizes were considered to be nonrepresentative because of the previous repair and cleaning of the prototype basin and the downstream channel.

The model was operated for 4 hours at Q = 3,940 cfs, both valves 100 percent open, reservoir elevation 6000, tailwater elevation 5715.3. The test resulted in minor damage to the basin floor between the end of the center wall and the end sill, Figure 15, corresponding to the damaged area in the prototype basin. Damage to the end sill could not be determined because some of the paint had peeled. It appeared that a large portion of the aggregate added during operation had been swept from the basin and sand had been pulled into the basin, Figures 14 and 15. Material was deposited everywhere on the horizontal floor but the largest amount was deposited between the end of the center wall and the end sill, Figure 15. Sandpiles were noted on the upstream side of the individual dentils.

The scour pattern in the sand bed immediately downstream from the stilling basin, Figure 15, indicated that material was being pulled toward the basin, and some sand entered the basin at both downstream corners.

Pressure fluctuations on the center wall, and accompanying vibration.--Pressure and vibration data were not analyzed for discharges of 500 and 960 cfs because jet penetration and turbulence along the center wall were insufficient to cause measurable variations. Measurements were made at Q = 1,840 cfs, 32 percent valve opening, and Q = 3,940 cfs, 100 percent valve opening, for three tailwater conditions as described earlier. Figure 16 shows the piezometer locations and Table 1 lists the reduced data. An accelerometer was attached near the top downstream corner of the right face of the center wall. The pressure measuring equipment included one transducer which was capable of measuring true differential pressure between two piezometers. This transducer was installed to measure the differential pressure between Piezometers C17 and C18. Only gage pressure (above atmospheric) was measured at Piezometers C5, C6, C11, C15, and C16. The remaining piezometers were in areas of relatively low turbulence and were not used. The number of available recording channels did not allow simultaneous measurements at all piezometers.

For Q = 1,840 cfs, the maximum differential pressures occurred on the upstream portion of the center wall. This also corresponded to the location of the maximum turbulence intensity according to the flow appearance. The vibration records were only qualitative, because the center wall was not modeled with respect to rigidity, and no attempt was made to calibrate the accelerometer. An important observation was that the frequency of vibration was essentially equal to the frequency of the fluctuation in differential pressure at Piezometers C17 and C18.

For Q = 3,940 cfs, the pressures were more evenly distributed along the center wall, which was also evidenced by the appearance of the turbulence. Slightly higher pressures occurred in the center section of the wall and there was a wider range in the frequency of pressure fluctuations along the wall, as compared to those recorded for 1,840 cfs. Also, there was not a well-defined agreement between the pressure frequency and the vibration frequency, though both were of the same order of magnitude.

An analysis by the Technical Engineering Analysis Branch showed that, in general, the frequency of pressure fluctuations matched the natural frequency of the prototype center wall. The analysis also showed that resonance of the wall would result in moments at the base of the wall several times greater than those used in the design.

Both valves 51 percent open, Q = 3,200 cfs, reservoir elevation 6101.6 (H = 382 feet), tailwater elevation 5715.0.--The model of the original configuration was also subjected to flows corresponding to operation at maximum reservoir elevation for a period of 4 hours. The stilling basin water surface was essentially level, with surges rising about 5 feet above the downstream end of the center wall. The surface boil was fairly evenly distributed from the end of the center wall to the downstream end of the basin, Figure 17. Wave heights in the downstream channel were about 1-1/2 feet from trough to crest. Moderate swirling occurred along the downstream face of the right outside wedge. Several pieces of coarse gravel placed in the basin were observed to circulate throughout the turbulence.

Scour in the downstream channel was localized at the end of the stilling basin, Figure 17. Some material was washed down the slopes on the outside of the basin walls. Only a few pieces of coarse sand were pulled into the horizontal portion of the stilling basin. The deposits of fine sand on the sloping apron and near the dentated end sill were apparently the result of sloughing of the channel banks during drainage of the model.

Both valves 100 percent open, Q = 4,720 cfs, reservoir elevation 6101.6 (H = 382 feet), tailwater elevation 5715.5.--The model was operated for 4 hours under these conditions, which represent the maximum operating conditions for the outlet works. The jets remained on the floor through the horizontal portion of the basin and occasionally turned upward near the downstream end of the viewing section. The water surface was essentially level and varied in height from near the top of the center wall to about 5 to 8 feet below the top of the wall. An intermittent boil rose near the downstream end of the center wall and a constant boil existed in the downstream portion of the basin, Figure 18. The downstream boil was fairly well distributed across the basin and varied from 5 to 8 feet in height, with a maximum height about 8 feet below the top of the outside walls. Some of the boil spilled over the sloping side walls at the downstream end of the basin.

Although about one-half handful of coarse sand and several pieces of coarse gravel had been placed on the sloping apron in the downstream portion of the basin before the test, no material could be seen circulating near the viewing window. There was moderate swirling along the downstream face of the right outside wedge. Waves in the downstream channel were about 2 feet high. Scour in the downstream channel was again limited to the area immediately downstream from the basin, Figure 18, and there was some down-slope washing of the channel slopes outside the basin walls. The coarse sand which was originally placed on the sloping apron was deposited in the horizontal portion of the basin. The coarse gravel was found immediately upstream and immediately downstream from the dentated end sill and one piece was lodged between a dentil and the right wall.

Right valve only 100 percent open, Q = 2,790 cfs, reservoir elevation 6101.6 (H = 382 feet), tailwater elevation 5714.8.--Limited observations were made for one-valve operation, Figure 19, which would be allowed only under emergency conditions when one valve was inoperative. Pressures on the center wall were not recorded, but there was no doubt that the combination of low tailwater and turbulence on one side of the wall and high static tailwater on the other side of the wall would cause severe loading conditions. Also, circulation in the downstream end of the basin would pull large amounts of sand and gravel from the downstream channel into the nonoperating side of the basin.

Maximum permissible discharge for operation with negligible jet penetration.--During the model investigation, it became necessary to operate the prototype outlet works to control the rising reservoir. It was desirable to operate the outlet works at the highest discharge which would not cause additional damage to the stilling basin. The reservoir was at approximately elevation 6000 at this time. A series of model tests were made to determine the optimum discharge for prototype operation.

A total discharge of 1,200 cfs, tailwater elevation 5714.1, resulted in jet penetration nearly to the bottom of the wedge slots in the model, Figure 20A, but no vortices formed along the wedge faces. Lightweight aggregate circulated slowly in the upstream portion of the basin, moving downstream on the surface and upstream near the bottom. Some pieces of aggregate were observed on the upper surfaces of the wedges. Spray overtopped the basin side walls, but flow into the downstream channel was calm. With a total discharge of 1,000 cfs, tailwater elevation 5714.0. Figure 20B, jet penetration was greatly reduced with only occasional pockets of turbulence moving through the wedge slots. Other conditions were essentially the same as with the 1,200-cfs discharge. Raising the tailwater elevation to 5716.0 further reduced the jet penetration, Figure 20C. Operation at reservoir elevation 5960 was very similar, Figure 20D. The 1,000-cfs discharge was considered acceptable for prototype operation, which is shown in Figure 20E. Inspection of the prototype stilling basin subsequent to this operation revealed no additional damage.

Summary of Results of Tests on the Original Configuration

Tests on the original stilling basin configuration indicated that abrasion damage to the prototype stilling basin occurred during the discharge of 1,840 cfs, 32 percent valve opening, reservoir elevation 5965. The model also showed that operation at 3,940 cfs, 100 percent valve opening, reservoir elevation 6000 caused additional abrasion damage and could have resulted in structural damage to the center dividing wall. The tests left no doubt that the model gave an adequate representation of the prototype performance and could be used to develop appropriate modifications.

First Modification, Wedges Removed, Center Wall Retained

Tests on the original configuration revealed that the most severe damage occurred to the prototype stilling basin during operation at a discharge of approximately 1,840 cfs, 32 percent valve opening, reservoir elevation 5965. The severe turbulence at the downstream end of the converging wedges caused violent circulation of abrasive material in the upstream portion of the basin and damage to the concrete surfaces. Therefore, the converging wedges were removed from the model and the center wall was extended upstream to the chute floor.

The model was operated at Q = 1,840 cfs, Figure 21A, and, in general, flow conditions were not as good as those observed with the wedges in place. Jet penetration was inadequate as evidenced by the very rough water surface in the basin and strong wave action in the downstream channel. Abrasive material added to the basin circulated slowly on the chute floor beneath the jets. Pressure fluctuations on the center wall were recorded with the tailwater at elevation 5714.4. The magnitude, frequency, and pattern of the pressure fluctuations, Table 2, were very similar to those observed for the original configuration. The vibration frequency was also similar, although a good comparison could not be made because of the reduced stiffness of the wall when the wedges were removed.

With the valves 100 percent open, Q = 3,940 cfs, reservoir elevation 6000, Figure 21B, the jets turned upward from the basin floor approximately 25 to 30 feet upstream from the corresponding point observed with the original configuration. A high boil formed near the downstream end of the center wall and at times overtopped the side walls (elevation 5728). Abrasive material circulated violently in the turbulence and on the chute floor beneath the jets. Wave action in the downstream channel was moderate. The resulting scour pattern on the channel bottom indicated a high downstream bottom velocity similar to that observed in the original configuration for 32 percent valve opening. It was also noted that the abrasive material circulated higher in the flow than it had with the wedges in place. Pressure fluctuations and vibrations on the center wall for tailwater elevation 5715.3, Table 2, were again very similar to those recorded with the wedges in place.

Second Modification, Center Wall Removed, Wedges Retained

Operation with the second modification was very similar to that with the center wall, except that the major turbulence due to jet expansion occurred along the outside walls. At 32 percent valve opening, Figure 22A, there were also noticeable surface boils along each outside wall. At Q = 3,940 cfs, Figure 22B, flow conditions were very similar to those in the original configuration. The discharge was increased to its maximum value to determine the acceptability of operation without the center wall. For Q = 4,720 cfs, 100 percent valve opening, reservoir elevation 6101.6, tailwater elevation 5715.5, Figure 22C, basin flow conditions were acceptable; however, the surface boil moved farther into the downstream channel. Only moderate transverse (perpendicular to the mean flow) surging was noted, and most of this occurred near the downstream end of the basin. With the tailwater at elevation 5722.0, Figure 22D, basin flow conditions were much rougher; high longitudinal surges overtopped the side walls and carried into the downstream channel and transverse surging was more noticeable.

With 2,790 cfs discharging through the left valve 100 percent open (right valve closed), reservoir elevation 6101.6, tailwater elevation 5714.8, Figure 22E, moderate transverse surging was observed. A surface boil formed along the left wall and spread to the right. Large amounts of riverbed material were drawn into the stilling basin. At tailwater elevation 5721.5, Figure 22F, basin flow conditions were very rough, particularly at the exit to the downstream channel. High surges frequently overtopped the outside walls.

Pressure fluctuations were recorded on the left outside wall, Table 3. (Piezometer locations are shown in Figure 23.) The pressure distribution was generally similar to that recorded in earlier tests on the center wall, except for the presence of subatmospheric pressures. The subatmospheric pressures were probably due to the water surface surges which caused momentary high velocities along the wall and should not cause concern with regard to cavitation. However, the magnitude of the fluctuations must be considered in designing the walls. The fluctuations were greatly increased during one-valve operation, which emphasizes the need for avoiding this type of operation. The subatmospheric pressures were minimum values; average values were at all times above atmospheric.

Third Modification, Wedges and Center Wall Removed, 3:1 Chute

The original slope without the wedges and center wall was not tested because the first modification indicated that an area of intense turbulence would continue to exist near the chute. The relatively flat chute of the third modification caused the jets to remain on the floor throughout the horizontal portion of the stilling basin. At the maximum discharge of 4, 720 cfs, Figure 24A, a large surface boil formed at the downstream end of the stilling basin. Flow conditions inside the stilling basin were quite good. One-valve operation at 2, 790 cfs, Figure 24B, resulted in very rough surface flow conditions at the downstream end of the basin; however, flow conditions within the basin were tolerable. Circulation of coarse sand which originated in the downstream channel was apparent. Operation at Q = 1, 840 cfs, Figure 25A, was acceptable. However, at Q = 3, 940 cfs, Figure 25B, the surface boil extended into the downstream channel.

Pressures on the left outside wall were measured for several representative discharges, gate openings, and reservoir elevations, Table 4. A wider fluctuation of pressures was measured with this modification than with the second modification because the walls were more directly exposed to the turbulence of the hydraulic jump.

A solid sill was installed midway between the bottom of the chute and the dentated end sill, in an attempt to turn the jet upward from the floor and reduce the surface turbulence at the downstream end of the basin. This sill, however, intercepted too much of the bottom flow and caused a high boil immediately above the sill which frequently overtopped the side walls. The sill was replaced by a series of baffle piers at the same location. Operation with the piers was satisfactory; however, exposure of the piers to high flow velocities and possible cavitation damage in this area of the basin floor would probably preclude their inclusion in the prototype.

Fourth Modification, 3:1 Chute with Center Wall

Operation with the center wall included showed some improvement over operation with the center wall removed. For Q = 1, 840 cfs, Figure 26A, flow conditions in the upstream portion of the basin were somewhat more stable. At Q = 3, 940 cfs, Figure 26B, the boil at the downstream end of the basin was less pronounced. At the maximum discharge of 4, 720 cfs, the hydraulic jump appeared to be more stable, the velocity along the basin floor was less, and the surface boil at the downstream end of the basin was smaller. However, intermittent longitudinal surging occurred and sometimes resulted in a low water surface on one side of the center wall with a high water surface on the other side.

Subatmospheric minimum pressures occurred along the center wall, Table 5, with wide fluctuations between maximum and minimum pressures; the wide fluctuations were probably due to the direct exposure of the center wall to the turbulence of the hydraulic jump. The center wall was less rigidly supported than when the wedges were in place and displayed resonant vibration. However, the stiffness of the model wall did not simulate the prototype wall and therefore would not necessarily be expected to represent the behavior of the prototype wall.

Fifth Modification, 2-1/2:1 Chute with Extended Center Wall

A 2-1/2:1 chute was installed and the center wall extended through the horizontal portion of the basin to the dentated end sill. Both valves were operated at openings of 25, 50, 75, and 100 percent under the maximum reservoir elevation 6101.5. Operation at 100 percent valve opening with a high tailwater was very rough; much smoother flow conditions prevailed at the low tailwater, Figure 27. At any tailwater elevation, the surface boil extended beyond the downstream end of the basin for valve openings of 75 and 100 percent. The slope of the chute appeared to be satisfactory for low tailwater operation and somewhat too steep for high tailwater operation. Rocks placed in the basin circulated violently wherever the turbulence was most intense. The discharge, valve opening, and tailwater depth determined the area of the basin in which the most intense turbulence occurred.

With a reservoir elevation of 6000.0, Figure 28, operation was much improved and could be considered satisfactory.

Chute blocks were installed at the bottom of the 2-1/2:1 chute, but no improvement in basin flow conditions was noted. The center wall extension was removed with the result that flow conditions in the downstream end of the basin appeared somewhat smoother while conditions in the upstream portion of the basin seemed rougher.

Summary of Previous Tests

The studies showed that confined zones of intense turbulence immediately downstream from the converging wedges could be eliminated by removal of the wedges. Also, turbulence could be more evenly distributed in the basin by installation of a 2-1/2:1 chute to induce lateral spreading of the annular jet and to maintain a relatively high velocity along the floor of the stilling basin. The maintenance of a high bottom velocity would ensure a "self-cleaning" basin so that abrasive material would not circulate. Several problems remained. First, at discharges near the maximum, the high bottom velocities resulted in surface turbulence at the downstream end of the basin. Bottom scour patterns indicated that this operation would result in channel material being pulled toward the stilling basin or into the basin to circulate during smaller discharges. Therefore, the problem of abrasive damage was alleviated but not eliminated.

Lengthening the basin was considered impractical because of problems in modifying the artificial slopes between the outlet works channel and the spillway channel. The second primary problem was that the center wall, in spite of modifications to the original basin design, continued to be subjected to dynamic forces which could cause structural damage.

Discharges above approximately 3,200 cfs caused the turbulence to extend beyond the end of the basin, with resulting large waves in the downstream channel.

The decision was therefore made to limit the maximum outlet works discharge to 3,200 cfs. This discharge, in combination with operation of the auxiliary outlet works and the 30-inch bypass valve, would provide the required outlet capacity. Additional tests were aimed at determining the necessity of the center wall and providing additional insurance against the entry of abrasive material into the stilling basin.

Sixth Modification, 2-1/2:1 Chute without Center Wall and with Miscellaneous Center Walls

The model was operated at a discharge of 3,200 cfs, reservoir elevation 6101.6, approximately 51 percent valve opening, tailwater elevation 5715.0, Figure 29. The jets moved along the floor to near the downstream end of the viewing section and at times turned upward before reaching the bottom of the chute. High surface boils occasionally overtopped the outside walls and there was some transverse surging in the basin. The jets influenced each other and the mainstream of the flow always moved along either the right or left side of the basin. Longitudinal surges carried through the basin into the downstream channel, causing fairly strong, well-defined waves. At tailwater elevation 5721.8, surface boils frequently overtopped the outside walls. The jets continued to influence each other and turned upward before reaching the bottom of the chute. Waves in the downstream channel were not as well defined and occurred randomly.

A 60-foot-long, 40-foot-high, 6-foot, 8-inch wide center wall was installed. Basin operation was certainly no better, and possibly worse, than that observed without the center wall. With the wall terminated 12 feet upstream from the bottom of the chute, basin flow conditions were improved, but a moderate surface boil existed at the downstream end of the basin for tailwater elevation 5715.0. At tailwater elevation 5721.8, flow conditions were similar to those with the longer wall. At the maximum discharge of 4,720 cfs, both high and low tailwater conditions, the jump profile was relatively flat and the turbulence near the downstream end of the basin was quite prominent.

A 12-foot-high, 4-foot-wide center wall, the same length as the original center wall, increased the stability of the basin flow by maintaining separation of the jets.

Seventh Modification, 2-1/2:1 Chute without Center Wall, Valves Tipped Additional 3°

The valves were tipped an additional 3° downward to determine the effect of increased impingement on the chute. Operation, Figure 30, was similar to that with a 3:1 chute; jet penetration and bottom velocity increased and a high boil formed at the downstream end of the channel. The jets moved from one side of the basin to the other, as demonstrated in the two right side views in Figure 30.

With discharges for which the turbulence was confined to the stilling basin, the scour pattern in the downstream channel indicated a relatively uniform velocity at the downstream end of the basin, Figure 30. However, under these conditions the basin was not "self-cleaning." With higher bottom velocities material was swept from the basin but the surface turbulence at the end of the basin resulted in material being pulled toward the basin or into the downstream portion of the basin, thus making this material available for circulation during lower discharges. There appeared to be no solution to this anomaly. It was decided to (1) retain the valves in their original position, (2) limit the outlet works maximum discharge to 3,200 cfs, as decided earlier, (3) remove the center wall, (4) eliminate the converging wedges and install a steel-lined 2-1/2:1 chute, (5) add a 1-foot thickness of new concrete to the basin floor and walls for repair and additional strength, and (6) reshape and pave the downstream channel for a distance of about 140 feet downstream from the basin to minimize the availability of abrasive material. This arrangement is shown in Figures 31, 32, and 33.

Recommended Design, Wedges and Center Wall Removed, Concrete Added to Basin Floor and Walls, Improved Downstream Channel

Several tests were performed on the recommended design to verify its acceptability. The tests included observation of flow conditions in the basin and in the downstream channel, recording of pressures on the channel paving near the end of the basin, development of a rock trap near the end of the basin, movement of rocks and sand in the basin and downstream channel, observation of abrasion caused by circulation of rocks and sand in the basin, and recording of pressures on the left wall of the stilling basin. The performance of the recommended design was evaluated primarily with test discharges of 3,200, 2,500, 2,000, and 1,500 cfs at reservoir elevation 6085 and normal tailwater. Elevation 6085 is the highest reservoir possible without operation of the spillway. Observations were also made for the maximum discharges of 4, 720 and 2, 790 cfs, both normal and maximum tailwaters, to evaluate basin performance under these severe conditions.

Flow conditions in the stilling basin and downstream channel. -- At the maximum allowable discharge of 3, 200 cfs, reservoir elevation 6085, tailwater elevation 5715. 0, Figure 33, flow conditions in the stilling basin were somewhat rougher then before the downstream paving was installed; however, they were still acceptable. Turbulence at the downstream end of the basin was confined to the surface most of the time. Occasional downstream surges were noted along the bottom at the downstream end of the basin.

Although not an expected operating condition, the maximum discharge capacity of 4, 720 cfs was observed with the maximum reservoir elevation of 6101. 6 and tailwater elevations 5715. 5 and 5722. 0, Figure 34. At the lower tailwater, turbulence was distributed throughout the basin and surface turbulence extended well into the downstream channel. At the higher tailwater elevation, conditions in the stilling basin were more unstable and strong longitudinal surges carried downstream. A pronounced surface boil occurred above the downstream end of the basin. However, wave action in the downstream channel was weaker than with the lower tailwater.

At a discharge of 2, 500 cfs, reservoir elevation 6085, tailwater elevation 5714. 6, Figure 35A, the jet velocity along the chute was less and the jets turned upward shortly after entering the horizontal portion of the basin. The surface velocity was relatively high at the downstream end of the basin and moderate waves occurred in the downstream channel.

At a discharge of 2, 000 cfs, reservoir elevation 6085, tailwater elevation 5714. 4, Figure 35B, the jets turned upward before reaching the end of the chute. A pronounced surface boil occurred above the end of the chute which resulted in longitudinal surges which carried into the downstream channel and caused moderate waves.

For 1, 500 cfs, reservoir elevation 6085, tailwater elevation 5714. 3, Figure 36, the surface boil above the end of the chute increased in size and some splashing occurred over the outside walls. Surface conditions in the downstream channel were somewhat smoother than for the higher discharges.

Operation of the left valve alone, 100 percent open, at a discharge of 2, 790 cfs, reservoir elevation 6101. 6, tailwater elevation 5714. 8,

Figure 37, resulted in expected very rough flow conditions and strong upstream flow along the right side of the basin. Surface turbulence extended into the downstream channel and caused strong wave action. Unsymmetrical operation of the outlets should be avoided.

Development of a rock trap at the downstream end of the stilling basin.--The design of the downstream paving originally included an 18-inch step on the downstream side of the solid end sill at the end of the stilling basin. Tests showed that the step allowed some rocks and sand to move into the stilling basin, Figure 38A. The material was placed on the paving before operation of the model. The depth of the trap was increased to 3 feet at the end sill, Figure 38B. The floor of the trap sloped upward to intersect the paving 20 feet downstream from the end sill. No material moved into the basin during operation, Figure 38C; therefore, the larger trap was recommended for the final design.

Pressures on the floor of the paving.--Pressure fluctuations on the paving floor were measured in the vicinity of the rock trap on the stilling basin centerline to determine the possible occurrence of damaging dynamic forces. Pressures recorded with electronic transducers showed a maximum fluctuation of 2.5 feet of water at a point approximately 20 feet downstream from the stilling basin for a discharge of 3,200 cfs, tailwater elevation 5715.0. For Q = 4,720 cfs, tailwater elevation 5715.5, the maximum pressure fluctuation at the same point was 3.5 feet. At tailwater elevation 5722.0, the maximum fluctuation was 2.5 feet. Pressures and piezometer locations are shown in Figure 39. The pressure fluctuations were too small to cause structural damage to the paving.

Velocity distribution at the downstream end of the stilling basin.--Velocities at the downstream end of the stilling basin (Station 24+00 on Figure 32) were measured with a miniature propeller meter for the full range of expected operating conditions and also for maximum capacity conditions. In general, these measurements revealed areas of instability and frequent upstream currents adjacent to the stilling basin walls and channel floors, Figure 40. The presence of sand and rock in many prototype stilling basins was explained by these data and the need for rock traps at the ends of the basins was supported. The sand erosion patterns noted earlier in this report were also explained by the velocity data. At high discharges, surface velocities were high and velocities generally decreased with depth. Surface turbulence resulted in bottom currents which circulated the bottom material with little or no overall downstream movement. At lesser discharges, velocities were more evenly distributed over the cross section, bottom velocities were higher, and bed material moved downstream. Velocities were not measured at the downstream end of the paved area. However, the length of the paving and the 18-inch offset at the end of the paving (see Figure 31) minimized the possibility of material entering the paved area at this point.

Material movement and abrasion tests.--Sand and gravel placed on the downstream paving moved toward the rock trap during operation of the outlet works. The extent of movement depended upon the magnitude of the discharge and the length of time of operation. Sand moved to the trap first. Sand and gravel in the trap exhibited a tendency to move away from the center of the trap towards the downstream corners of the stilling basin. The model indicated that no material would enter the stilling basin unless the rock trap became full.

Material was placed in the stilling basin to compare its movement and abrasion with those of the original design. The surfaces of the basin were again painted with enamel which dried to a hard finish. The model was operated for approximately 4 hours (about 14 hours prototype time) at a discharge of 3,200 cfs, reservoir elevation 6085, tailwater elevation 5715.0. One handful of pea gravel and one handful of angular gravel were placed in the basin prior to operation. During operation, the material could be heard striking the walls of the basin. After the test, most of the material was found in the rock trap at the downstream end of the basin, but several pieces of the angular gravel remained in the basin. Abrasion was evidenced throughout the horizontal floor of the basin, on the basin walls to a maximum height of about 25 feet, and on the lower portion of the chute. There were no concentrated areas of extensive abrasion. After 5-1/2 hours operation (about 19 hours prototype) at Q = 2,500 cfs, reservoir elevation 6085, tailwater elevation 5714.6, abrasion was limited primarily to the upstream portion of the basin, Figure 41. All material remained in the basin, and a large portion of it was found on the chute. Heaviest abrasion occurred at the intersection of the chute and floor and lighter abrasion occurred approximately 60 feet up the chute and 60 feet along the basin floor and walls.

Similar abrasion occurred after a 4-hour test at Q = 2,000 cfs, reservoir elevation 6085, tailwater elevation 5714.4. Heaviest damage again occurred at the intersection of the chute and basin floor, but over a smaller area than for 2,500 cfs.

Operation at 1,500 cfs, reservoir elevation 6085, tailwater elevation 5714.3, resulted in minor abrasion to the basin walls adjacent to the chute. All material collected near the bottom of the chute.

Pressures on the left wall.--Magnitudes and frequencies of pressures on the left wall of the stilling basin are shown in Table 6. Piezometer locations are shown in Figure 42.

Data were recorded for discharges of 4,720, 3,200, 2,500, 2,000, and 1,500 cfs with several reservoir heads and tailwater elevations. For the maximum discharge of 4,720 cfs, tailwater elevation 5715.5, the maximum pressure and maximum fluctuation in pressure occurred about 25 feet (prototype) downstream from the intersection of the chute and the horizontal floor. For all other discharges and tailwaters, the maximum pressures and fluctuations occurred upstream from the bottom of the chute.

Comparisons between these pressures and those measured with a 3:1 sloping chute (third modification, Table 4) can be made only for the maximum discharge capacity of 4,720 cfs. The distributions of pressures are generally similar. Variations are noted in the values of the maximum and minimum peaks but no specific trends can be observed.

Pressures on the chute.--Figures 43 and 44 illustrate the magnitude of pressures on the recommended chute for discharges of 3,200 and 4,720 cfs. The measurements showed a wide fluctuation in the pressures due to impact of the hollow jets. The magnitude and frequency of fluctuations indicate the need for careful attachment of the protective steel lining. The slight subatmospheric minimums at Piezometer 3 are not unusual but are only momentary peaks which cannot cause cavitation damage.

APPENDIX

Review of Damage to Other Stilling Basins

Problems similar to those experienced at Navajo Dam have occurred at other projects in the recent past.

R. H. Berryhill[3/] described damage which occurred to the outlet works stilling basin for Texarkana Dam, Texas, in 1957. The outlet works consists of two 20-foot-diameter conduits which discharge into a hydraulic jump stilling basin. The basin includes two rows of baffles and an end sill. The flow is separated by a thin, 35-foot-high concrete center wall. The maximum flow passed by the outlet works was 24,000 cfs, to May 1963 (the time of writing of Berryhill's paper). Sometime during 1957, the downstream 24 feet of the center wall failed at the base of the wall and fell to one side. The failure of the wall was apparently caused by inadequate bond at the construction joint near the base of the wall and by

3/"Experience with Prototype Energy Dissipators," R. H. Berryhill, Paper 3521, Proceedings, ASCE, Journal of the Hydraulics Division, May 1963.

the fatigue failure of the vertical reinforcing bars. The basin also exhibited erosion, particularly at the baffle blocks, which was apparently caused by circulation of boulders found afterwards in the basin. Operating personnel felt that the boulders had been pushed over the walls of the basin by fishermen and sightseers.

Berryhill also described damage to the outlet works basin for Belton Dam, Texas. This basin is also the hydraulic-jump type, with two rows of baffles and a solid end sill. The maximum discharge to May 1963 was 12,800 cfs. In the fall of 1960, the basin was unwatered and some of the baffle blocks were found to be eroded sufficiently to expose the reinforcing steel. Substantial erosion was noted throughout the basin floor. About 295 cubic yards of sand, gravel, and large rocks were found in the basin and the riprap in the exit channel had been displaced. The abrasion damage was attributed to the circulation of the large rocks. Many of the rocks were believed to have been thrown into the basin by visitors. The possibility that some of the material might have originated in the exit channel was also raised. The basin was cleaned and repaired, the displaced riprap was replaced, and a chain link fence was installed at the training walls.

In a discussion of Berryhill's paper, W. E. Wagner and M. A. Jabara, 4/ described abrasion damage observed in the spillway and outlet works basin at Anderson Ranch Dam, Idaho. Examination showed a large deposit of rocks and coarse sand in the basin which was believed to have come from the excavation slopes along each side of the spillway. The reinforcing steel in the chute blocks was exposed and the upstream two-thirds of the basin floor was roughened. The damage was repaired with epoxy mortars.

Wagner and Jabara also described the operation of the outlet works stilling basin for Glendo Dam, Wyoming. The basin includes large chute blocks and baffle piers, as determined from hydraulic model studies. In April 1958 the outlet works was operated at 25 percent of the capacity of 10,000 cfs. An audible periodic thump was noted in the stilling basin and vibrations were felt in the basin and powerplant walls. Skindiver inspection of the flow surfaces showed evidence of cavitation damage immediately downstream from the gates and on the sides of the center chute block in the extreme left bay. Operation continued for several months, then the basin was unwatered and inspected. Severe cavitation damage was noted on the sides of the center chute block in each bay, along the flared walls, and in the bottom portion of the stoplog grooves.

The baffle piers were undamaged and the concrete in the wall between the outlet works basin and the powerplant tailrace showed no damage

4/ Proceedings of ASCE, Journal of the Hydraulics Division, January 1964.

from the violent vibration. The chute blocks, baffle piers, flared walls, and stoplog grooves were modified with the aid of hydraulic model studies. The thumping and vibration have continued during subsequent prototype operation, but no cavitation damage has occurred.

In August 1963, the hollow-jet valve stilling basin at Trinity Dam, California, was unwatered and inspected. The outlet works consists of two 84-inch hollow-jet valves with a maximum discharge capacity of about 8,600 cfs under a maximum static head of 475 feet. The observed damage to the stilling basin gave evidence of abrasion. More than 100 cubic yards of gravel, cobbles, and boulders were found in the basin. The material had apparently entered the basin from the outlet channel during spillway discharges the previous winter. Abrasion damage to the chute and wedge surfaces was minor. Appreciable damage occurred on the basin floor and near the bottom of the walls. The extent of wall damage decreased with increasing distance from the floor and the abrasion damage to the floor and walls increased in the downstream direction. The unlined outlet channel also exhibited damage.

The center dividing wall of the basin failed along a horizontal construction joint about 20 feet above the basin floor. The reinforcing steel indicated that the failure was due to fatigue. The remaining lower portion of the wall showed well-developed horizontal flexure cracks near the bottom of the wall on both sides and a vertical crack near the center. Spalling of the concrete at the base of the wall indicated compressive failure. No cracking was noted in the floor slab.

The abrasion damage was repaired with epoxy mortar and new reinforced concrete, and the center wall was replaced with a thicker wall, which included the remaining portion of the original wall in its center. Some additional minor abrasion damage has occurred since the repairs were made.

Table 1

INSTANTANEOUS PRESSURES ON CENTER WALL (PROTOTYPE VALUES)
ORIGINAL CONFIGURATION

Piezometer number	Discharge cfs	Valve opening %	Tailwater elevation	Pressures Max (ft of water)	Pressures Min (ft of water)	Pressures Ave (ft of water)	Pressure frequency cps	Vibration frequency cps
C5	1,840	32	5718.5	53.8	24.4	36.4	4.5	3.8
C6				40.0	32.5	35.8	5.3	
C11				39.1	33.2	36.3	5.8	
C12				37.9	33.4	35.8	5.1	
C15				25.4	22.2	24.1	3.5	
C16				26.1	20.3	23.9	4.2	
C17 & C18*				2.6	-2.3	0.4	3.6	
C5			5714.4	51.4	16.6	31.0	3.3	3.9
C6				37.6	23.2	31.3	4.9	
C11				35.8	23.2	30.4	5.5	
C12				34.1	25.6	31.0	4.9	
C15				22.6	13.6	19.8	3.5	
C16				21.4	16.5	19.1	3.8	
C17 & C18				2.9	-2.5	1.2	3.5	
C5			5712.0	48.0	10.0	26.8	3.6	3.0
C6				46.0	19.0	28.0	4.0	
C11				37.6	21.8	26.8	4.1	
C12				31.5	22.9	28.0	4.9	
C15				20.8	11.5	16.6	2.9	
C16				19.8	11.4	16.7	3.2	
C17 & C18				2.4	-6.9	-1.2	3.0	
C5	3,940	100	5721.5	43.6	11.8	26.8	3.3	3.8
C6				37.6	25.6	32.8	4.2	
C11				47.2	26.2	33.4	6.6	
C12				46.6	29.2	35.8	5.3	
C15				37.0	11.2	25.0	3.2	
C16				35.2	19.6	25.4	3.5	
C17 & C18				8.1	-10.8	-0.6	2.7	
C5			5715.3	35.2	16.6	25.0	3.6	3.6
C6				33.8	17.2	25.6	5.2	
C11				48.4	13.0	28.0	6.9	
C12				53.8	3.2	28.0	4.8	
C15				27.4	6.4	16.0	2.3	
C16				24.4	8.8	16.0	6.9	
C17 & C18				16.8	-17.4	0.0	6.9	
C5			5712.5	29.4	8.8	19.6	4.2	4.6
C6				34.0	8.8	22.0	5.9	
C11				52.6	11.2	25.6	8.2	
C12				46.6	3.4	24.4	5.3	
C15				24.4	-0.2	13.6	3.5	
C16				30.4	-1.2	13.6	3.5	
C17 & C18				20.2	-23.4	0.0	3.5	

Piezometer locations on Figure 16.
*Differential pressure. Plus and minus signs denote relative direction of unbalanced head.

Table 2

INSTANTANEOUS PRESSURES ON CENTER WALL (PROTOTYPE VALUES)
FIRST MODIFICATION, WEDGES REMOVED, CENTER WALL RETAINED

Piezometer number	Discharge cfs	Valve opening %	Tailwater elevation	Pressures Max	Min	Ave	Pressure frequency cps	Vibration frequency cps
				ft of water				
C5	1,840	32	5714.4	30.4	17.2	28.0	6.6	4.2
C6				31.6	27.8	29.8	4.1	
C11				31.4	27.3	28.0	3.2	
C12				30.4	26.2	28.0	5.0	
C15				20.2	14.2	17.5	1.7	
C16				20.1	15.5	17.9	5.0	
C17 & C18				3.1	-3.2	-0.3	3.8	
C5	3,940	100	5715.3	54.4	35.2	24.4	5.2	3.8
C6				36.4	6.4	25.6	3.9	
C11				41.2	20.8	30.4	2.7	
C12				40.0	22.0	31.6	3.5	
C15				23.2	18.4	20.8	1.7	
C16				26.8	8.8	20.8	4.7	
C17 & C18				7.2	-9.6	0.0	3.3	

Piezometer locations on Figure 16.

Table 3

INSTANTANEOUS PRESSURES ON LEFT WALL (PROTOTYPE VALUES)
SECOND MODIFICATION, CENTER WALL REMOVED, WEDGES RETAINED

Piezometer number	Discharge cfs	Valve opening %	Tailwater elevation	Pressures Max ft of water	Pressures Min ft of water	Pressures Ave ft of water	Pressure frequency cps
L1	1,840	32	5714.4	7.6	-8.0	0.4	5.7
L2				26.8	12.9	19.6	8.7
L3				13.0	4.0	8.5	5.1
L4				26.2	13.0	19.6	12.9
L5				11.2	3.3	8.8	8.4
L6				23.2	15.8	20.6	8.7
L7				33.7	30.9	32.6	3.3
L1	3,940	100	5715.3	11.2	-1.4	5.2	6.4
L2				21.5	14.8	18.2	10.1
L3				9.4	2.2	5.8	6.5
L4				20.8	8.2	17.8	13.0
L5				9.3	3.5	7.4	10.1
L6				21.4	14.2	17.2	10.1
L7				34.0	18.4	28.0	2.6
L1	4,720	100	5715.5	8.8	-8.0	0.4	6.8
L2				20.6	11.4	16.3	10.8
L3				8.2	-3.8	4.6	7.9
L4				24.4	1.6	14.6	13.0
L5				14.2	-5.0	6.4	14.4
L6				28.0	0.4	16.0	13.0
L7				38.8	10.0	24.4	2.7
L1	4,720	100	5722.0	19.0	-0.2	10.0	7.2
L2				28.0	18.7	22.7	10.8
L3				13.6	4.6	8.8	6.2
L4				40.0	5.8	19.0	16.6
L5				19.6	5.8	10.6	12.3
L6				28.6	8.2	22.0	12.3
L7				33.6	19.6	31.6	3.0
L1	2,790	100*	5714.8	12.4	-17.6	1.6	8.4
L2				23.9	11.4	17.2	13.7
L3				14.8	-5.6	5.2	6.5
L4				35.2	-10.4	14.8	15.9
L5				13.0	-5.0	7.0	13.7
L6				38.8	-4.4	14.8	9.4
L7				55.6	9.6	26.8	2.5
L1	2,790	100*	5721.5	17.2	-7.4	6.4	6.2
L2				27.3	16.2	22.9	10.1
L3				19.6	0.4	10.6	6.5
L4				48.4	2.8	22.0	16.6
L5				20.8	4.6	11.8	10.8
L6				33.3	10.7	22.0	13.7
L7				53.2	14.8	32.8	3.0

Piezometer locations on Figure 23.
*Left valve only.

Table 4

INSTANTANEOUS PRESSURES ON LEFT WALL (PROTOTYPE VALUES)
THIRD MODIFICATION, 3:1 SLOPE, WEDGES AND CENTER WALL REMOVED

Piezometer number	Discharge cfs	Valve opening %	Tailwater elevation	Pressures Max ft of water	Pressures Min ft of water	Pressures Ave ft of water	Pressure frequency cps
L1	1,840	32	5714.4	25.6	-3.2	7.6	1.7
L2				40.0	7.0	16.0	2.9
L3				16.6	-3.8	7.6	1.4
L4				26.5	8.2	17.8	2.6
L5				11.8	2.8	7.6	5.0
L6				22.2	15.1	19.1	6.1
L7				32.1	30.4	31.6	2.2
L1	3,940	100	5715.3	22.0	-17.6	-2.8	1.2
L2				19.6	10.6	15.3	3.2
L3				8.2	0.4	4.0	1.2
L4				26.8	-0.8	16.0	2.5
L5				9.4	1.6	5.2	5.3
L6				21.4	5.8	16.0	5.6
L7				37.6	13.6	22.0	2.2
L1	4,720	100	5715.5	22.0	7.0	1.6	2.0
L2				20.8	11.2	15.4	3.6
L3				5.2	-1.4	2.2	1.3
L4				37.0	-14.0	13.0	2.5
L5				8.2	-1.4	2.8	4.5
L6				29.2	1.6	13.6	4.3
L7				36.4	10.0	15.6	1.7
L1	4,720	100	5722.0	32.4	-21.2	10.0	1.4
L2				29.2	13.6	21.4	3.3
L3				13.6	4.6	10.0	1.6
L4				34.0	-2.0	20.8	3.3
L5				18.4	7.6	14.0	5.8
L6				28.6	13.4	23.8	5.2
L7				46.0	16.0	38.0	1.9
L1	2,790	100*	5714.8	35.0	-18.8	2.8	1.4
L2				22.0	10.0	14.8	3.2
L3				14.2	-2.0	2.2	1.9
L4				49.0	-20.0	16.0	2.9
L5				11.8	-2.0	2.8	4.9
L6				28.0	-5.6	11.2	4.6
L7				58.0	4.0	24.4	2.0
L1	2,790	100*	5721.5	46.0	-18.8	10.0	3.5
L2				50.8	0.4	22.0	2.7
L3				23.2	-2.0	10.0	1.3
L4				76.0	-5.0	25.0	3.0
L5				19.6	1.6	10.6	5.3
L6				44.8	9.8	20.8	4.1
L7				50.8	17.2	32.8	2.0

Piezometer locations on Figure 23.
*Left valve only.

Table 5

INSTANTANEOUS PRESSURES ON CENTER WALL (PROTOTYPE VALUES)
FOURTH MODIFICATION, 3:1 CHUTE WITH CENTER WALL

Piezometer number	Discharge cfs	Valve opening %	Tailwater elevation	Pressures Max	ft of water Min	Ave	Pressure frequency cps
C3	1,840	32	5714.4	22.0	13.6	17.2	2.9
C4				39.4	5.8	15.4	4.5
C9				31.6	7.0	17.6	2.0
C10				23.2	17.2	20.5	4.2
C15				20.8	17.2	19.3	7.2
C16				21.3	15.5	18.6	4.6
C17 & C18				3.4	-2.0	0.0	4.3
C3	3,940	100	5715.3	34.0	4.0	16.0	3.6
C4				48.4	-11.6	11.2	4.9
C9				43.6	-8.0	16.0	1.9
C10				23.2	8.8	17.2	3.5
C15				23.2	11.2	16.0	5.8
C16				24.4	8.8	16.0	4.6
C17 & C18				12.0	-13.2	0.0	2.2
C3	4,720	100	5715.5	36.4	5.2	14.8	4.5
C4				43.6	-21.2	7.6	6.3
C9				34.0	5.2	10.0	1.9
C10				25.6	0.4	14.8	3.5
C15				14.8	-45.2	-6.8	4.6
C16				23.2	4.0	14.8	3.5
C17 & C18				19.2	-22.8	0.0	4.5
C3	4,720	100	5722.0	46.0	-6.8	19.6	4.5
C4				55.6	-11.6	19.6	5.3
C9				46.0	4.4	22.0	1.9
C10				52.0	-1.0	22.0	4.6
C15				34.0	-10.0	20.2	6.0
C16				34.9	-10.0	20.1	4.9
C17 & C18				19.2	-20.2	0.0	3.8

Piezometer locations on Figure 16.

Table 6

INSTANTANEOUS PRESSURES ON LEFT WALL OF RECOMMENDED STILLING BASIN PROTOTYPE VALUES

	Piezometer number	Max	Min	Ave	Ave Max	Ave Min	Pressure frequency
Q = 3,200 cfs	1	+38.6	-15.4	+7.4	+19.4	-1.0	6.1
Reservoir elevation 6101.6	2	+27.8	-8.2	+9.2	+17.0	+2.6	6.1
Tailwater elevation 5715	3	+51.4	-4.0	+20.0	+35.0	+8.0	5.2
	4	+29.6	+0.2	+13.4	+21.8	+6.2	4.9
	5	+44.6	+3.8	+23.0	+29.0	+12.2	7.5
	6	+35.0	+15.2	+26.6	+31.4	+20.6	6.9
Q = 3,200 cfs	1	+71.0	-20.2	+19.4	+29.0	+12.2	5.2
Reservoir elevation 6101.6	2	+47.0	+0.2	+19.4	+27.8	+11.0	5.8
Tailwater elevation 5721.8	3	+52.4	+4.4	+30.8	+36.2	+23.0	5.5
	4	+33.8	+5.0	+21.8	+25.4	+18.2	3.5
	5	+39.2	+15.8	+33.2	+36.2	+29.0	6.6
	6	+37.0	+31.6	+35.0	+36.8	+31.6	6.4
Q = 3,200 cfs	1	+50.6	-19.0	+7.4	+14.6	+0.2	5.2
Reservoir elevation 6085	2	+[illegible]2.6	-4.6	+11.0	+17.0	+2.6	5.5
Tailwater elevation 5715	3	+48.4	-4.0	+20.0	+29.0	+12.6	5.2
	4	+24.2	+0.2	+13.4	+20.0	+7.4	4.0
	5	+44.6	+6.2	+22.4	+32.6	+12.2	6.9
	6	+34.4	+15.2	+26.6	+31.4	+20.6	6.9
Q = 4,720 cfs	1	+19.4	-4.6	+6.2	+14.6	+0.8	6.6
Reservoir elevation 6101.6	2	+13.4	+1.4	+6.8	+9.8	+3.8	7.2
Tailwater elevation 5715.5	3	+30.8	-13.0	+18.6	+29.0	+5.0	4.6
	4	+15.8	+0.2	+7.4	+12.2	+3.8	4.0
	5	+45.8	-4.6	+19.4	+31.4	+5.0	6.6
	6	+32.6	-4.6	+21.8	+26.4	+9.8	5.8
Q = 4,720 cfs	1	+67.4	-28.6	+12.2	+35.0	+0.2	5.5
Reservoir elevation 6101.6	2	+44.6	-6.4	+14.6	+26.6	+2.6	6.4
Tailwater elevation 5722	3	+59.0	+0.2	+26.0	+44.6	+8.6	5.2
	4	+36.8	+3.8	+17.0	+26.6	+7.4	3.5
	5	+47.0	+3.8	+26.6	+36.2	+15.8	6.4
	6	+42.8	+18.2	+31.4	+36.2	+24.2	6.1
Q = 2,500 cfs	1	+54.2	-9.4	+9.8	+25.4	+0.2	6.9
Reservoir elevation 6085	2	+41.0	-5.8	+11.0	+20.6	+2.6	6.9
Tailwater elevation 5714.6	3	+44.0	+2.0	+20.0	+29.0	+11.0	6.1
	4	+29.6	+1.4	+12.2	+20.6	+3.8	3.5
	5	+37.4	+9.2	+24.2	+30.2	+17.0	7.2
	6	+29.6	+23.6	+26.6	+29.0	+28.5	8.1
Q = 2,000 cfs	1	+38.6	-8.2	+9.8	+17.0	+2.6	5.5
Reservoir elevation 6085	2	+29.0	-1.6	+14.0	+20.6	+7.4	6.1
Tailwater elevation 5714.4	3	+36.2	+15.2	+25.4	+30.2	+22.4	5.8
	4	+18.2	+7.4	+14.6	+17.6	+11.0	4.0
	5	+29.7	+23.0	+26.4	+29.0	+24.4	7.2
	6	+29.8	+24.8	+26.6	+27.2	+25.0	9.2
Q = 1,500 cfs	1	+32.0	+3.8	+13.4	+21.8	+7.4	6.6
Reservoir elevation 6085	2	+23.0	+5.0	+13.4	+19.4	+9.8	7.2
Tailwater elevation 5714.3	3	+32.6	+18.2	+26.6	+29.6	+23.6	5.8
	4	+18.2	+11.0	+14.6	+17.0	+12.2	6.4
	5	+28.5	+25.2	+27.1	+28.3	+25.6	7.2
	6	+28.0	+26.4	+27.2	+27.8	+26.6	8.4

Piezometer locations are shown on Figure 42.

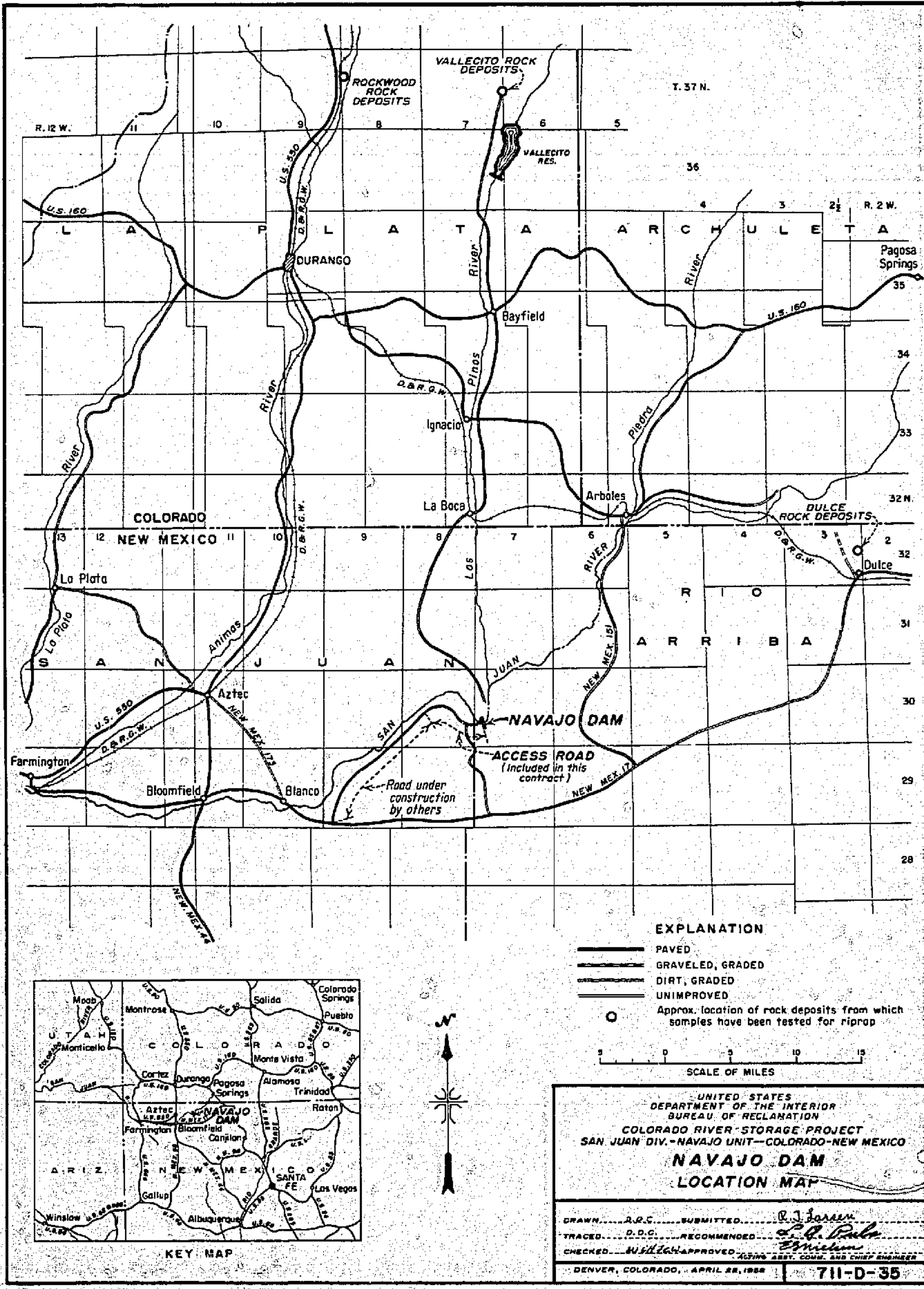
Table 7

METRIC EQUIVALENTS OF IMPORTANT QUANTITIES

Feature	English units	Metric units
Dam height above riverbed	388 feet	118 meters
Dam length at crest	3,650 feet	1,113 meters
Dam volume	26 million cubic yards	20 million cubic meters
Size of outlet works hollow-jet valves	72-inch diameter	182.88 centimeters
Discharge capacity of outlet works	4,720 cfs	133.6 m^3/sec
Design discharge for modified stilling basin	3,200 cfs	90.6 m^3/sec
Maximum head on valves	382 feet	116 meters
Modified stilling basin depth	49 feet	14.94 meters
Stilling basin length (with sloping apron)	200 feet	61 meters
Modified stilling basin width at floor	35 feet 2 inches	10.72 meters

Note: Where approximate or nominal English units are used to express a value the corresponding metric units are also approximate or nominal. Where precise English units are used the corresponding metric units are expressed as equally significant values.

FIGURE 1
REPORT HYD. 573

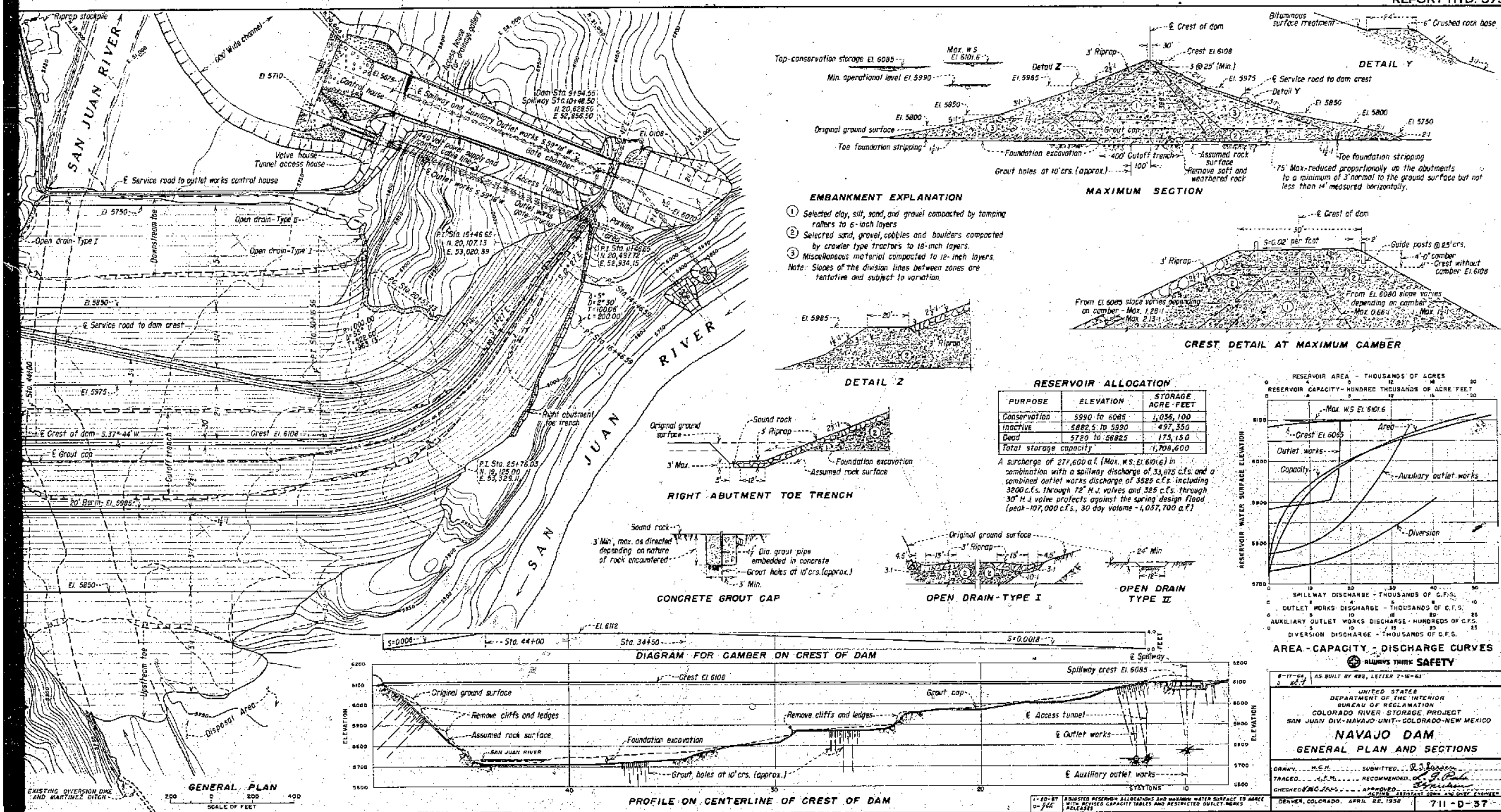


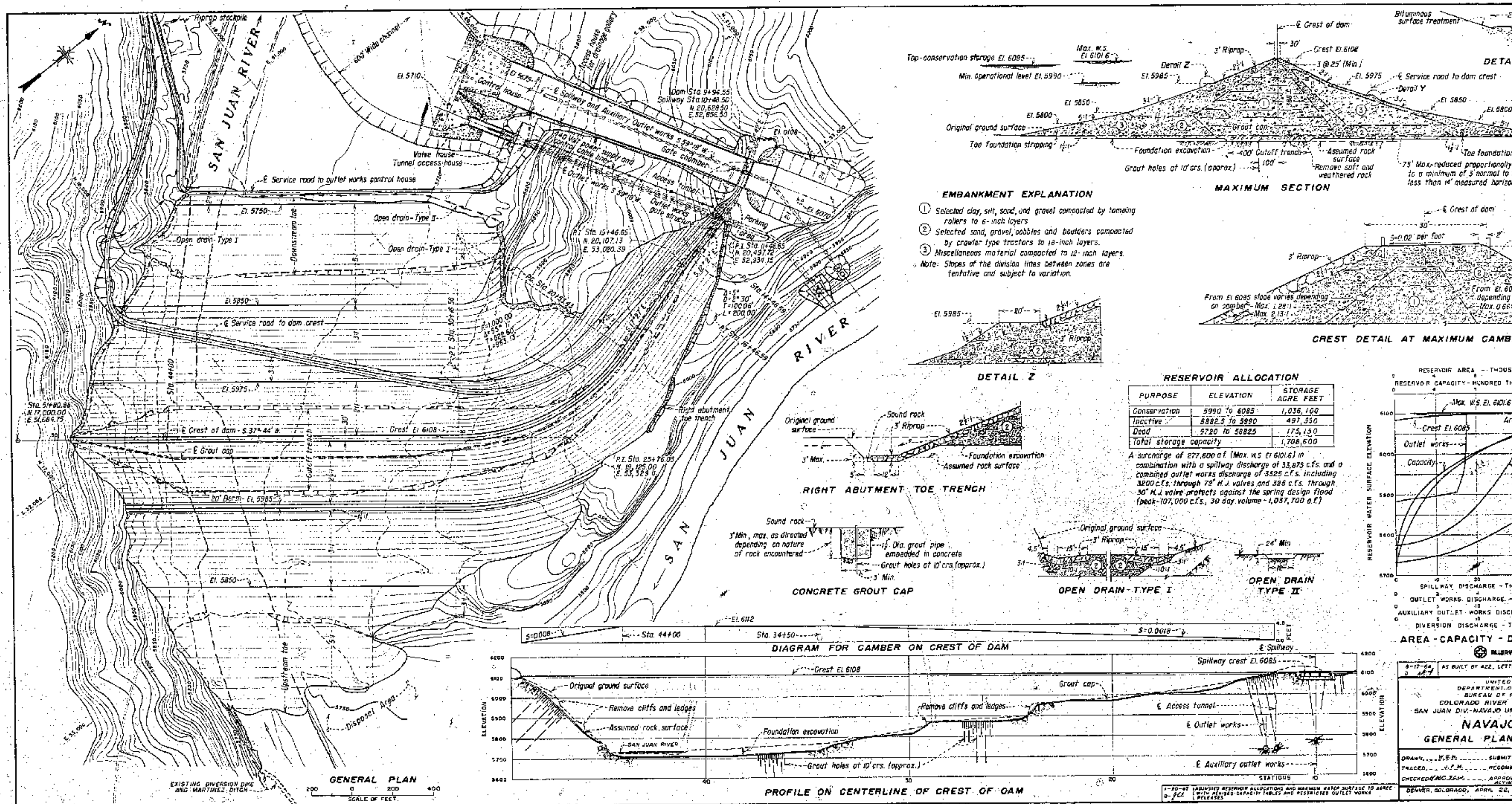
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT—COLORADO-NEW MEXICO

NAVAJO DAM
LOCATION MAP

DRAWN ....D.D.C.... SUBMITTED ....R. J. Larsen
TRACED ....D.D.C.... RECOMMENDED ....
CHECKED ....W.H.R.... APPROVED .... ACTING ASST. COMM. AND CHIEF ENGINEER

DENVER, COLORADO, APRIL 22, 1958 | 711-D-35


GENERAL PLAN
SCALE OF FEET
SAN JUAN RIVER
MAXIMUM SECTION
DETAIL Y
DETAIL Z
EMBANKMENT EXPLANATION
(1) Selected clay, silt, sand, and gravel compacted by tamping rollers to 6-inch layers
(2) Selected sand, gravel, cobbles and boulders compacted by crawler type tractors to 18-inch layers.
(3) Miscellaneous material compacted to 12-inch layers.
Note: Slopes of the division lines between zones are tentative and subject to variation.
CREST DETAIL AT MAXIMUM CAMBER
RIGHT ABUTMENT TOE TRENCH
CONCRETE GROUT CAP
OPEN DRAIN-TYPE I
OPEN DRAIN TYPE II
RESERVOIR ALLOCATION
PURPOSE | ELEVATION | STORAGE ACRE-FEET
Conservation | 5990 to 6085 | 1,036,100
Inactive | 5882.5 to 5990 | 497,350
Dead | 5720 to 58825 | 175,150
Total storage capacity | | 1,708,600
A surcharge of 277,600 a.f. (Max. W.S. El. 6101.6) in combination with a spillway discharge of 33,875 c.f.s. and a combined outlet works discharge of 3525 c.f.s. including 3200 c.f.s. through 72" H.J. valves and 325 c.f.s. through 30" H.J. valve protects against the spring design flood (peak-107,000 c.f.s., 30 day volume-1,037,700 a.f.)
AREA-CAPACITY-DISCHARGE CURVES
DIAGRAM FOR CAMBER ON CREST OF DAM
PROFILE ON CENTERLINE OF CREST OF DAM
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT-COLORADO-NEW MEXICO
NAVAJO DAM
GENERAL PLAN AND SECTIONS
DENVER, COLORADO, APRIL 22, 1958
711-D-37



PURPOSE	ELEVATION	STORAGE ACRE FEET
Conservation	5990 to 6085	1,036,100
Inactive	5882.5 to 5990	497,350
Dead	5720 to 5882.5	175,150
Total storage capacity		1,708,600

FRAME 2

FIGURE 3
REPORT HYD. 573

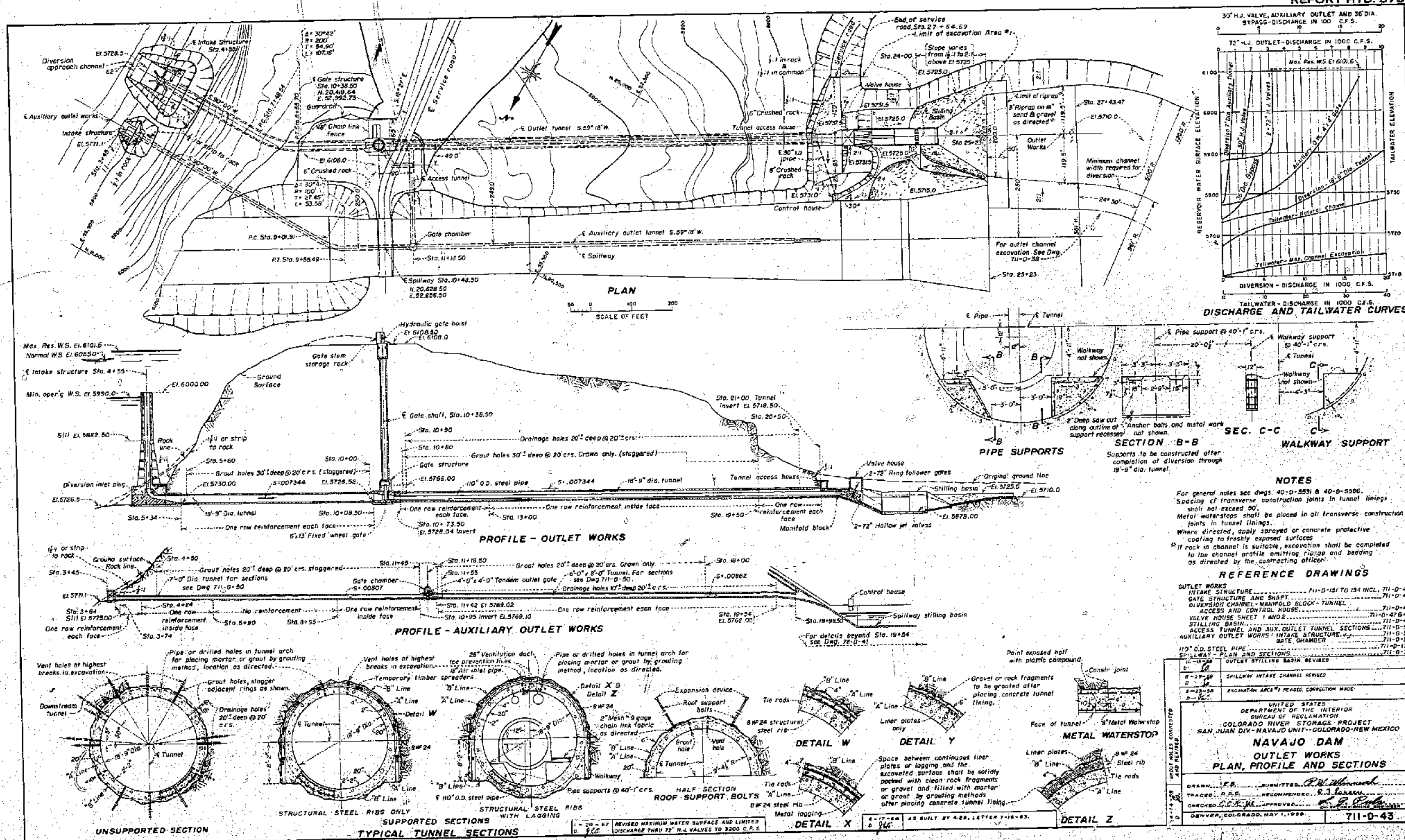
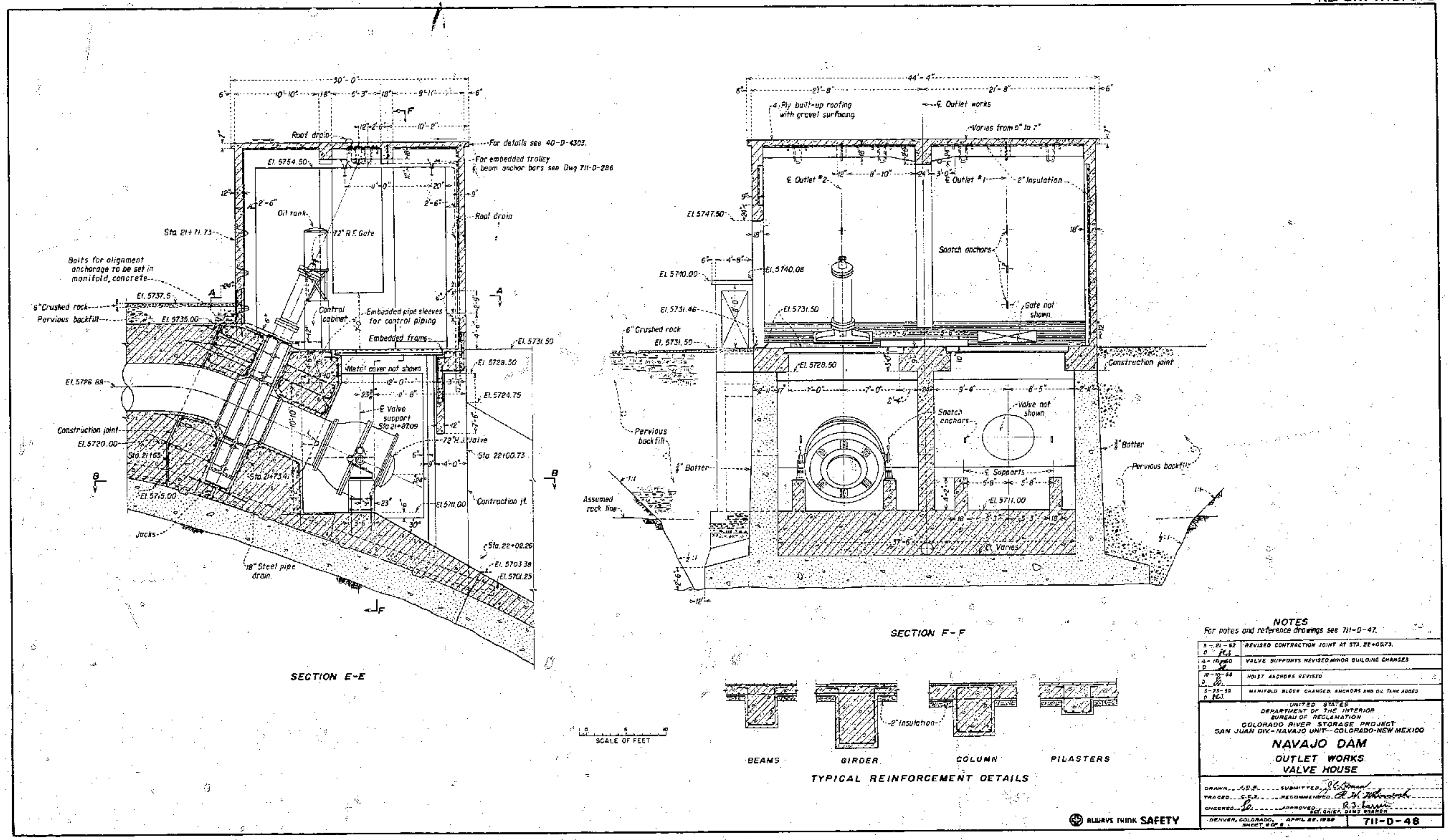
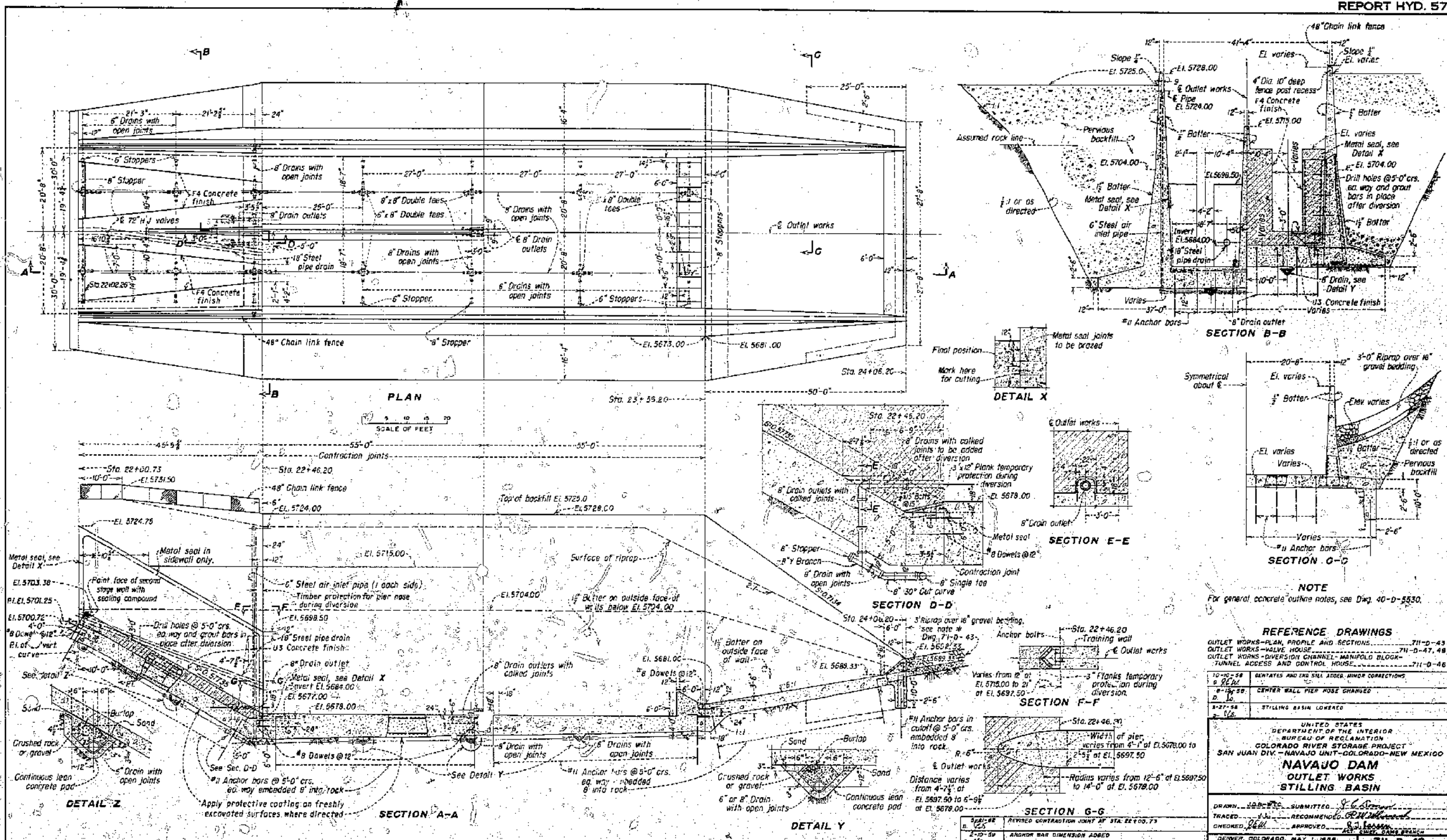
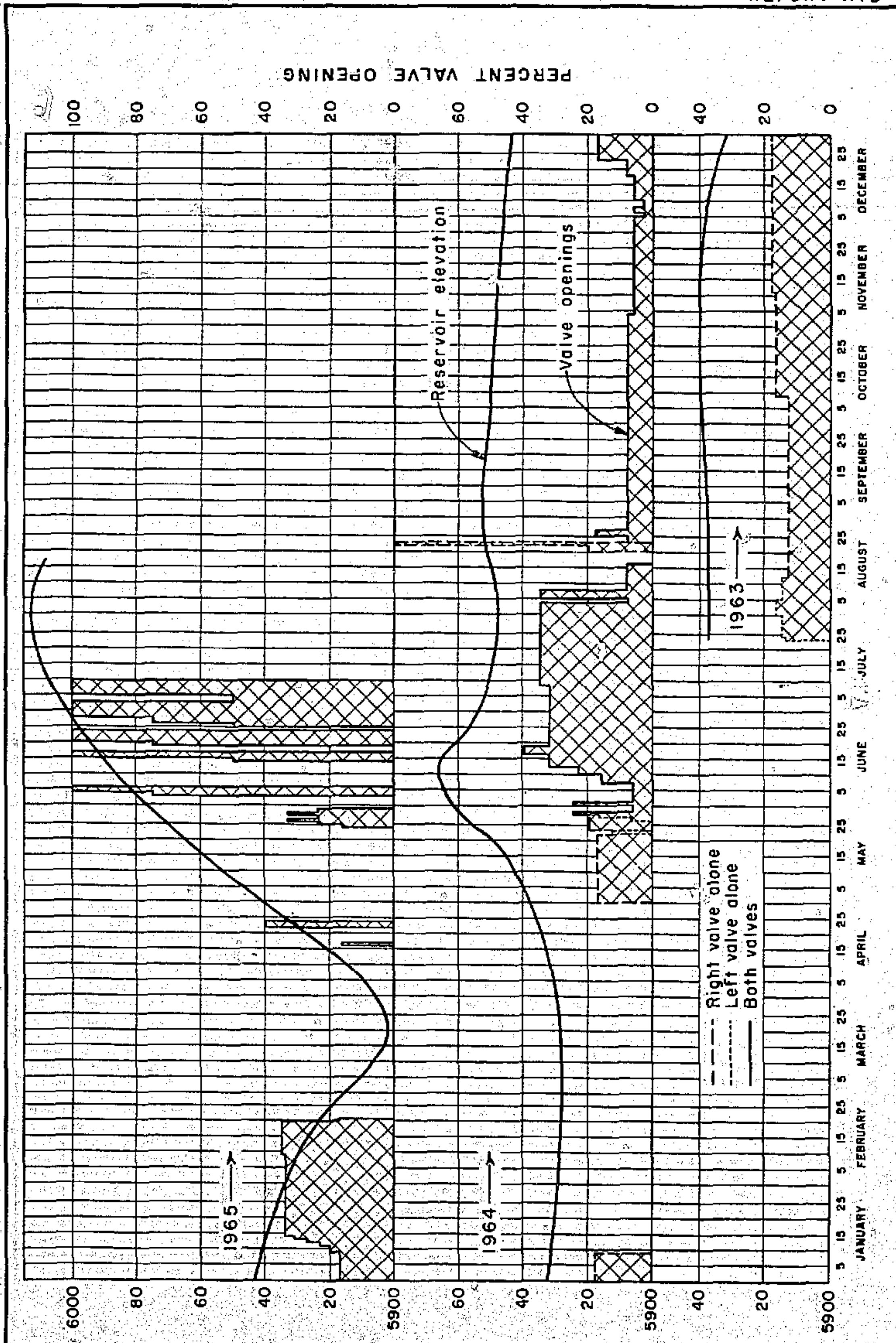


FIGURE 4
REPORT HYD. 573

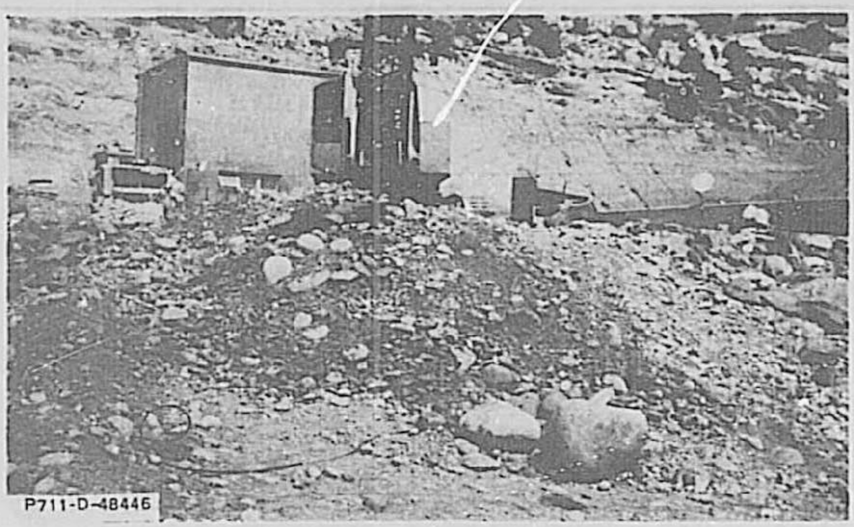



PLAN
SCALE OF FEET
SECTION A-A
SECTION B-B
DETAIL X
SECTION D-D
SECTION E-E
SECTION G-G
SECTION F-F
SECTION G-G
DETAIL Y
DETAIL Z
NOTE
For general concrete outline notes, see Dwg. 40-D-5530.
REFERENCE DRAWINGS
OUTLET WORKS-PLAN, PROFILE AND SECTIONS ... 711-D-43
OUTLET WORKS-VALVE HOUSE ... 711-D-47, 48
OUTLET WORKS-DIVERSION CHANNEL-MANIFOLD BLOCK-TUNNEL ACCESS AND CONTROL HOUSE ... 711-D-46
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT-COLORADO-NEW MEXICO
NAVAJO DAM
OUTLET WORKS
STILLING BASIN
DENVER, COLORADO, MAY 1, 1958
711-D-49



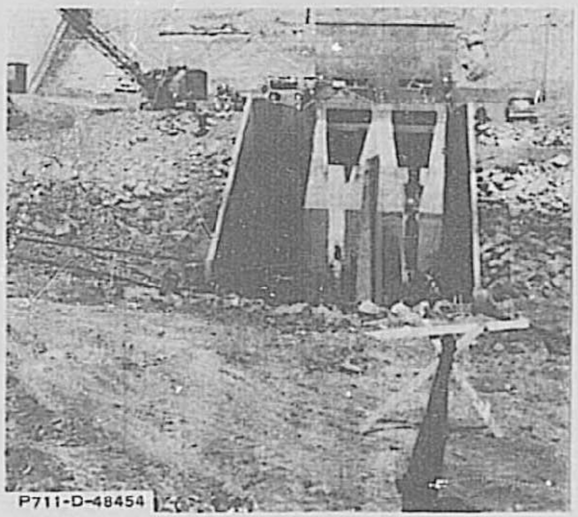
NAVAJO DAM OUTLET WORKS
RECORD OF PROTOTYPE OPERATION

Figure 7
Report Hyd-573



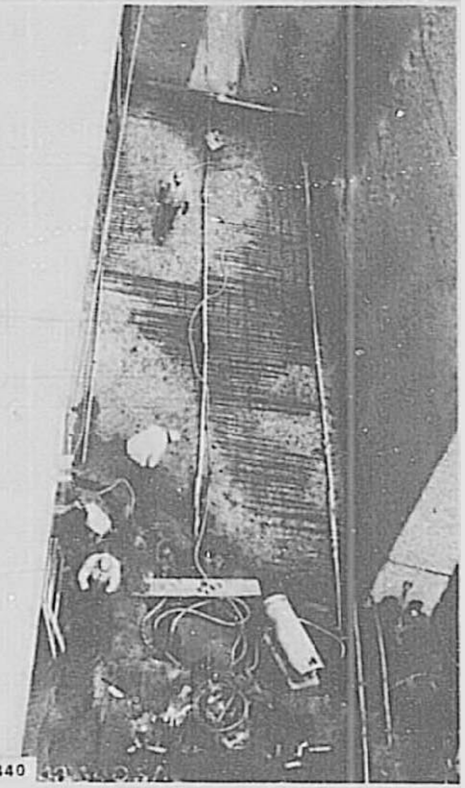
P711-D-48446

Material removed from stilling basin.



P711-D-48454

Overall view of damaged basin.

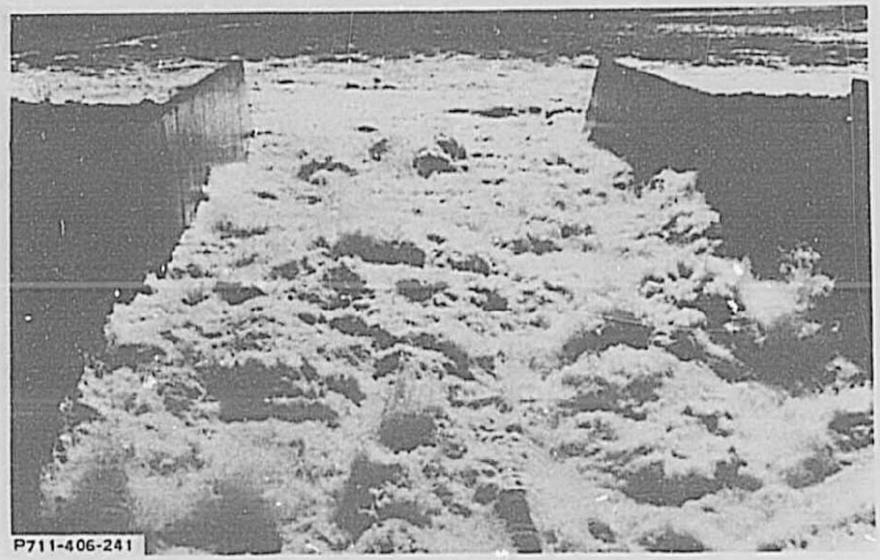


P711-D-48440

Damage in right bay.

NAVAJO DAM OUTLET WORKS

Original Configuration
Damage in Prototype Stilling Basin

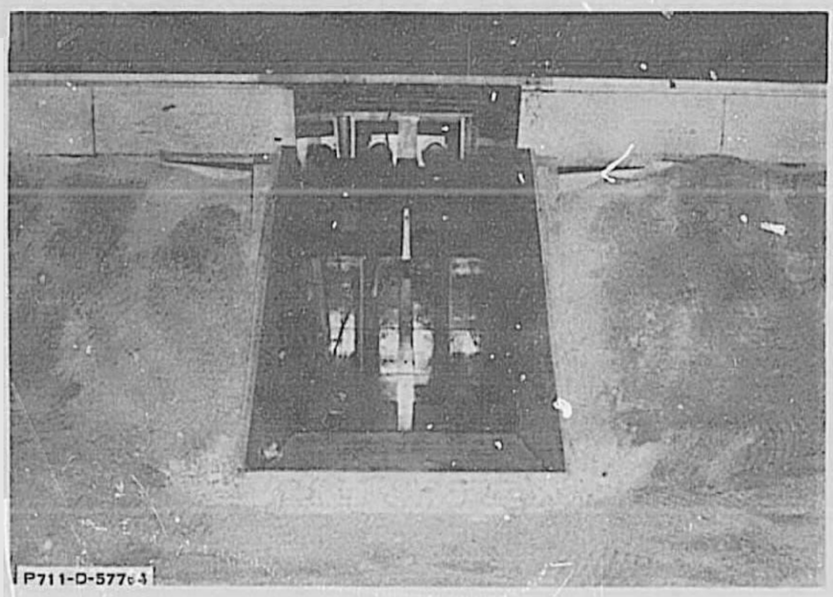


Discharge ≃ 3,900 cfs
Valve opening = 100 percent
Reservoir elevation 5998.2
Tailwater elevation ≃ 5715

NAVAJO DAM OUTLET WORKS

Original Configuration
Prototype Operation

Figure 9
Report Hyd-573

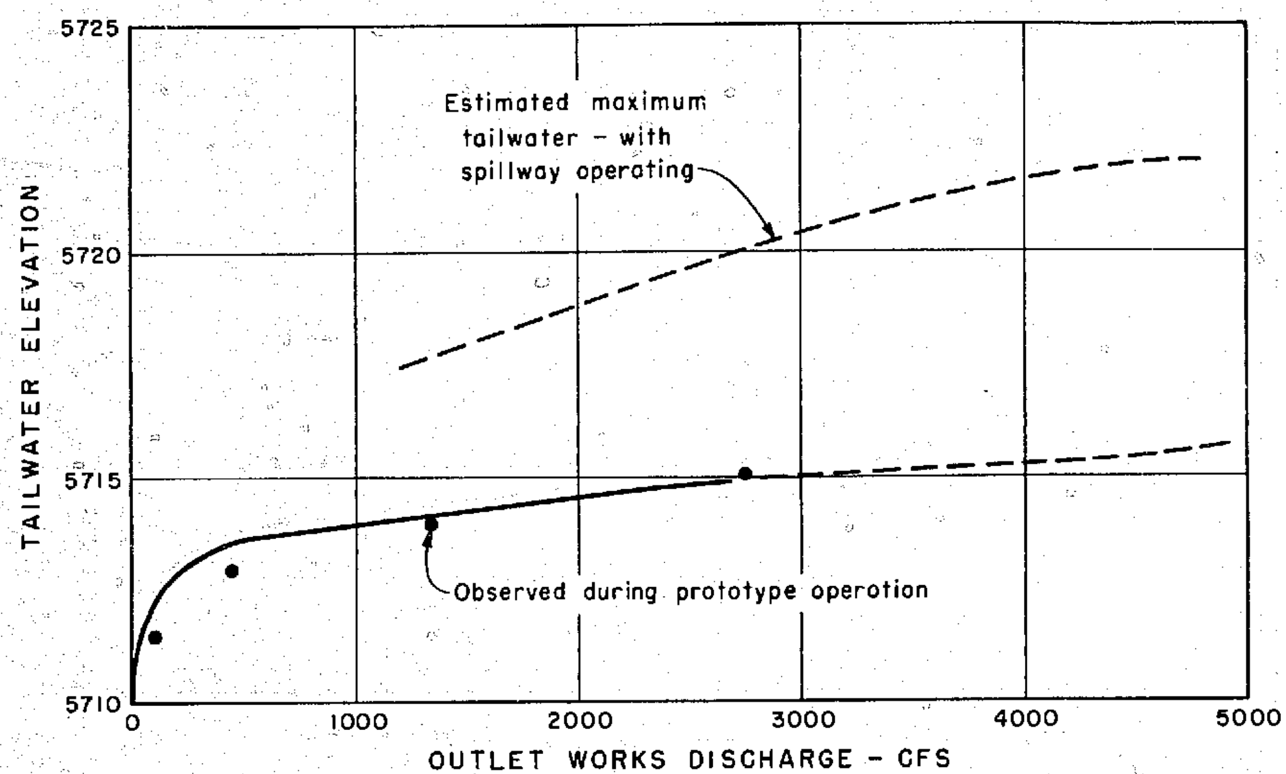


Original configuration of stilling basin.

Original configuration of downstream channel area.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

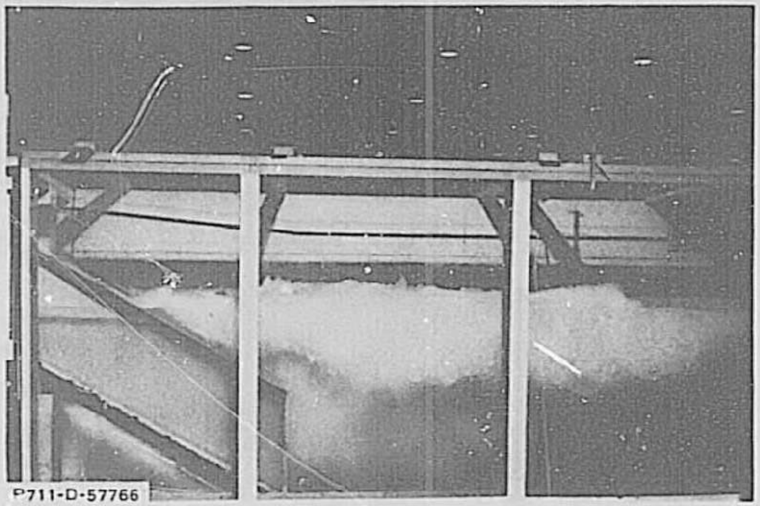
721



NAVAJO DAM OUTLET WORKS

TAILWATER CURVES FOR MODEL STUDY

FIGURE 10
REPORT HYD-573

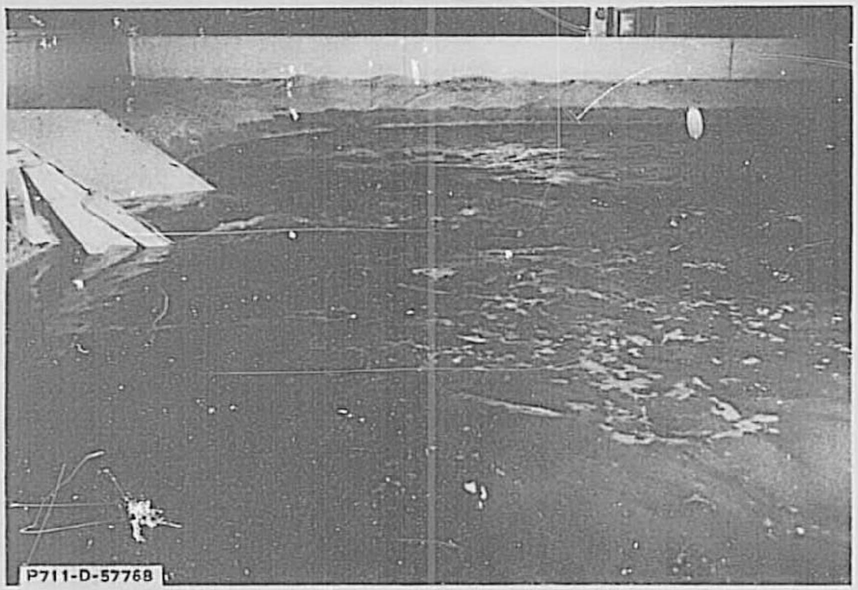


P711-D-57766

Right-side view of stilling basin.

P711-D-57767

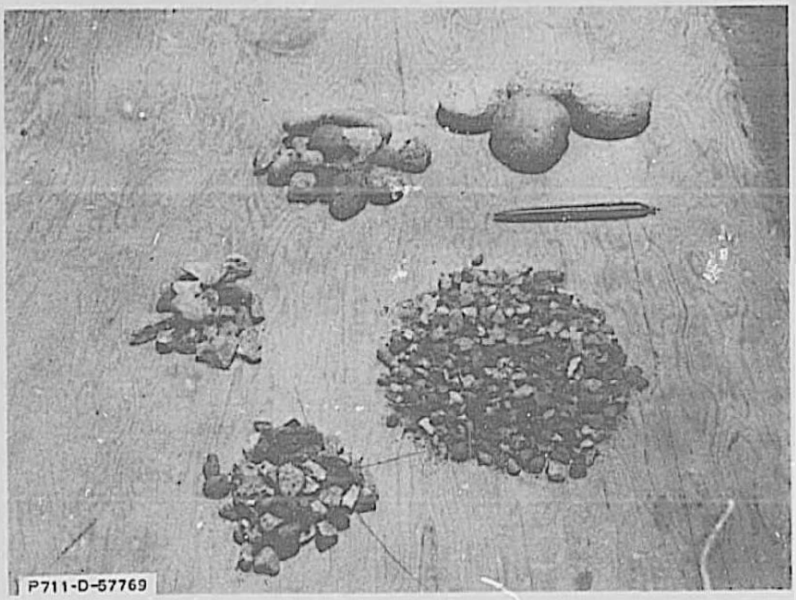
Downstream cha



P711-D-57768

Flow conditions in downstream channel.

Q = 1, 840 cfs
Both valves 32 p
Reservoir eleva
Tailwater elevat



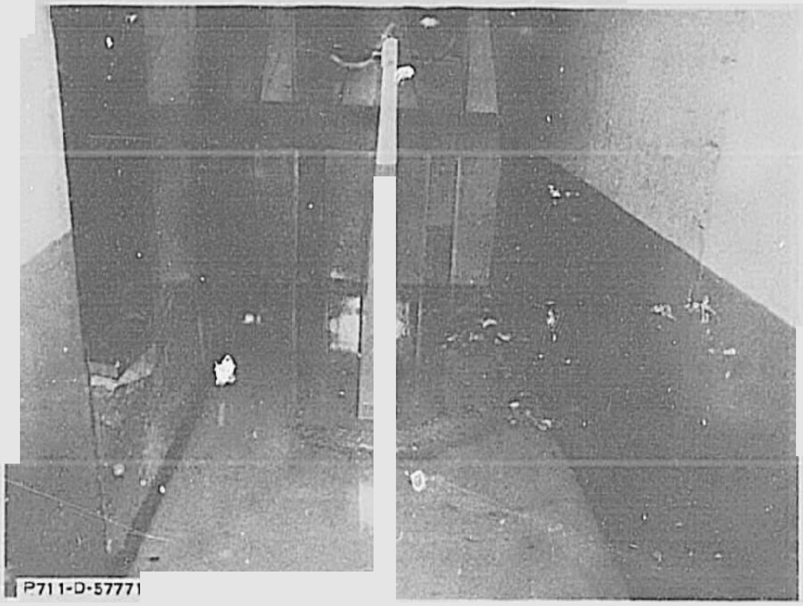
A. Material placed in basin for abrasion test.

B. Sand pulled into basin during abrasion test.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Original Configuration

Figure 13
Report Hyd-573

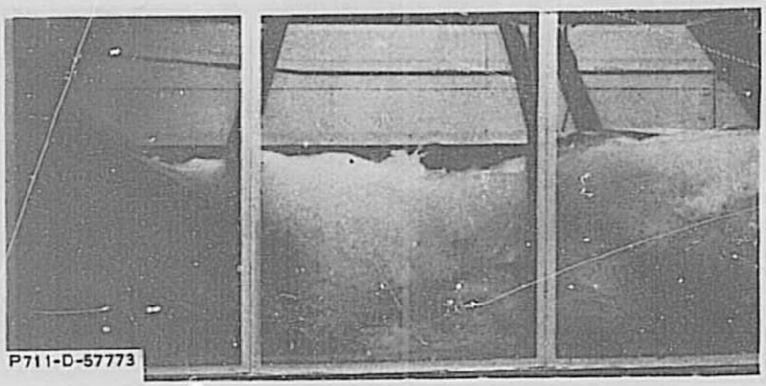


Material in stilling basin and damage after 4 hours operation at Q of 1,840 cfs, reservoir elevation 5965, both valves 32 percent open, tailwater elevation 5714.4.

Damage in right bay of stilling basin.

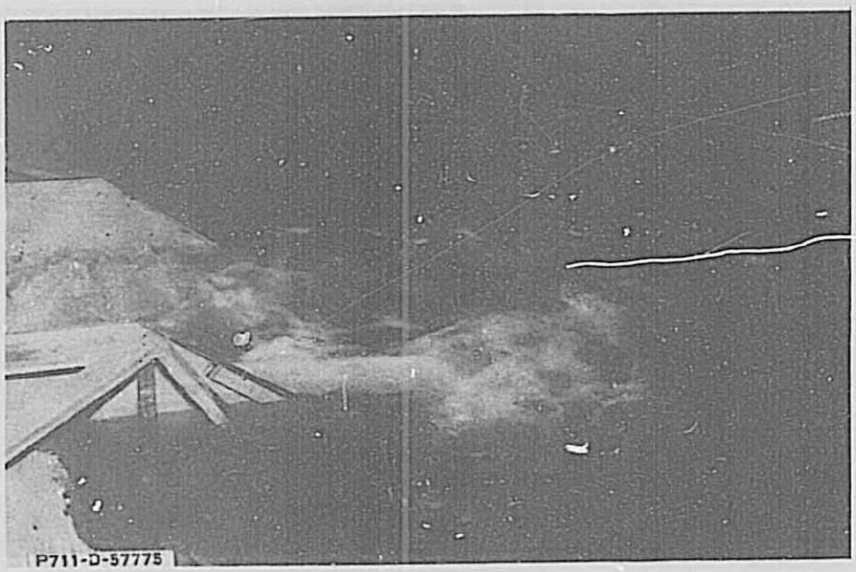
NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Original Configuration

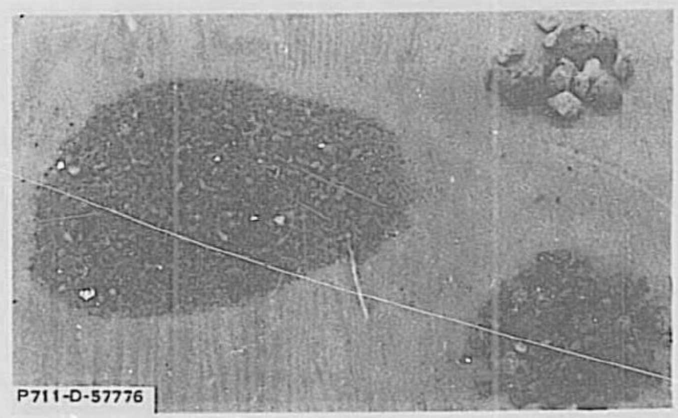


Right side view of stilling basin. Q = 3, 940 cfs, both valves open 100 percent, reservoir elevation 6000, tailwater elevation 5715.3.

View of stilling basin from near right valve.



Flow conditions in downstream channel.



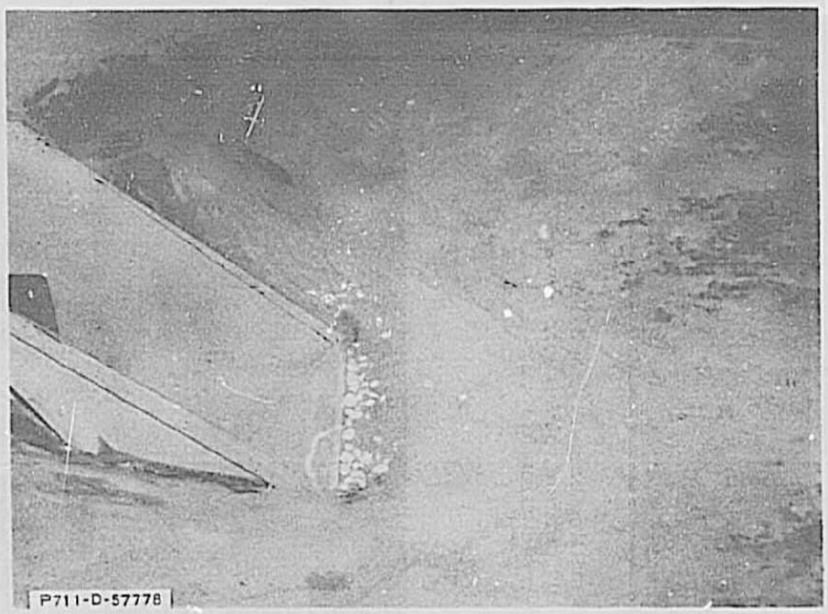
Material placed in basin before test and material pulled into basin during test.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Original Configuration

Figure 15
Report Hyd-573

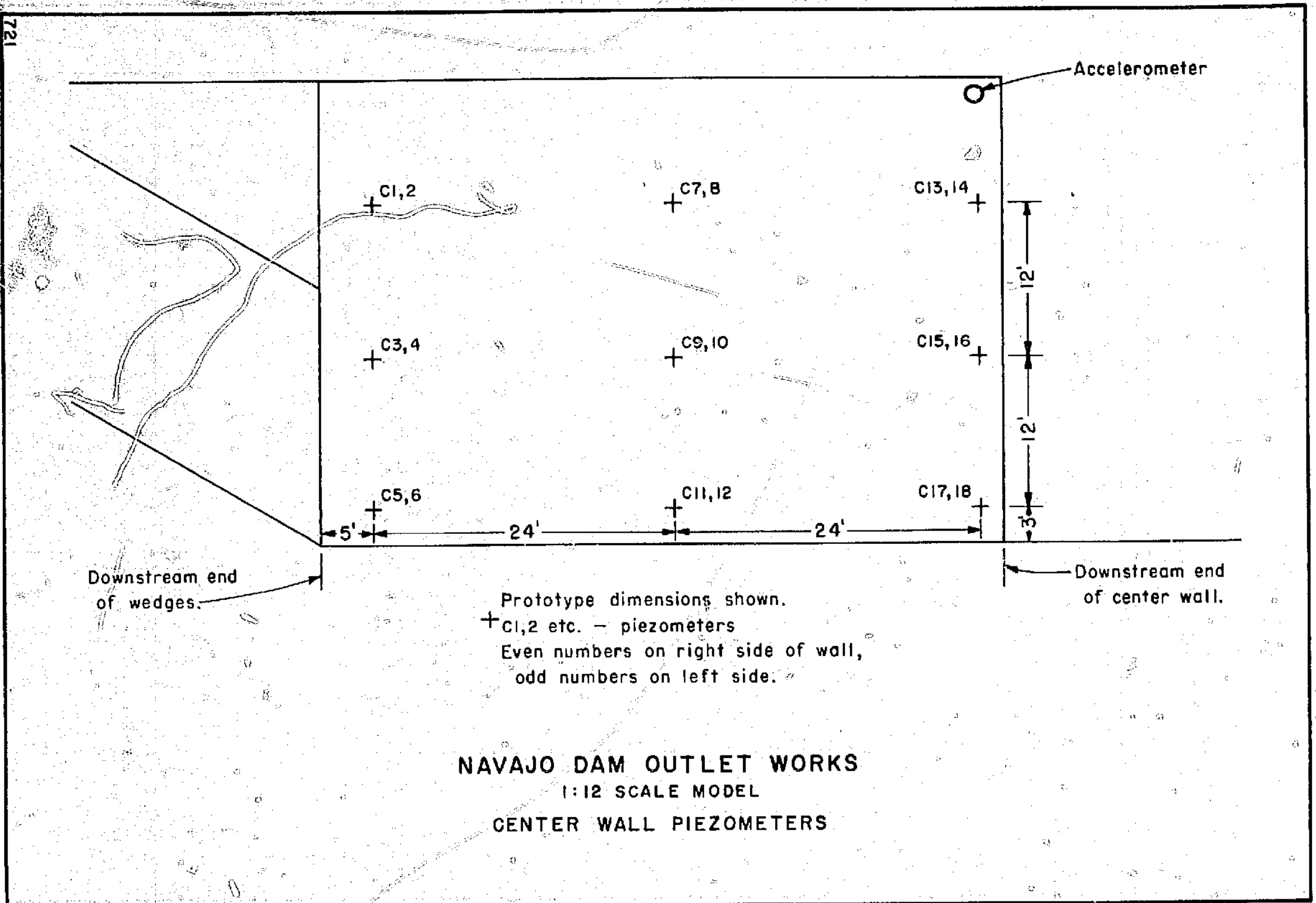
Material in stilling basin after 4 hours operation
at Q of 3, 940 cfs (Figure 14).



Condition of downstream channel after 4 hours
operation at Q of 3, 940 cfs (Figure 14).

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

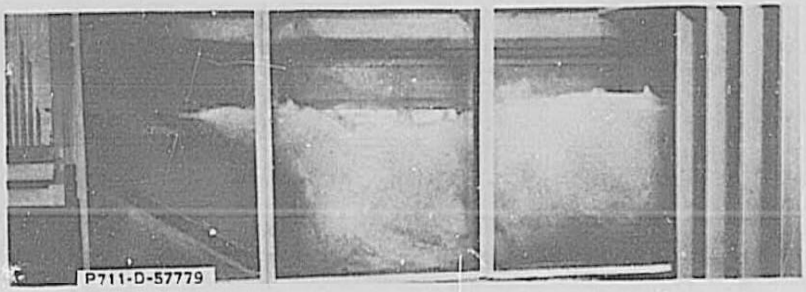
Original Configuration



Prototype dimensions shown.
+C1,2 etc. – piezometers
Even numbers on right side of wall, odd numbers on left side.

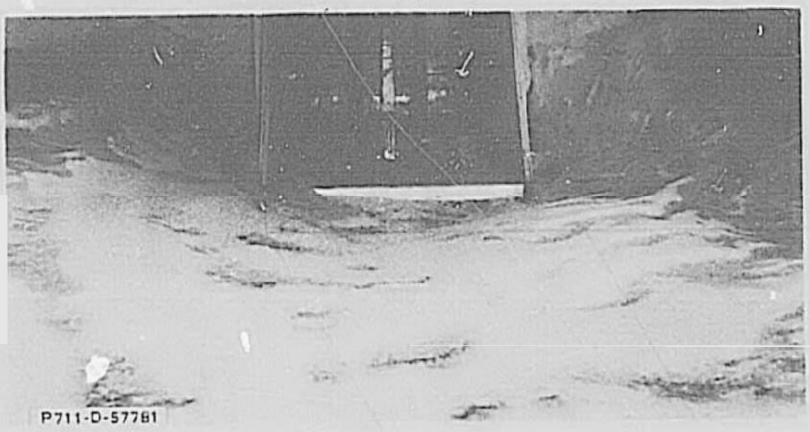
NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL
CENTER WALL PIEZOMETERS

Figure 17
Report Hyd-573



Right-side view of stilling basin. Q = 3,200 cfs, both valves 51 percent open, reservoir elevation 6101.6, tailwater elevation 5715.0.

Flow conditions in downstream channel.

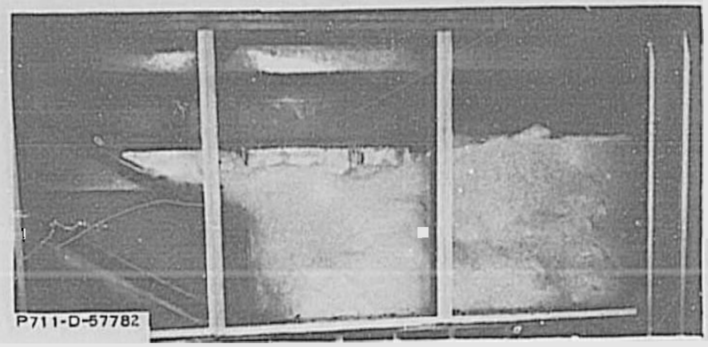


Condition of downstream channel after 4 hours at Q of 3,200 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

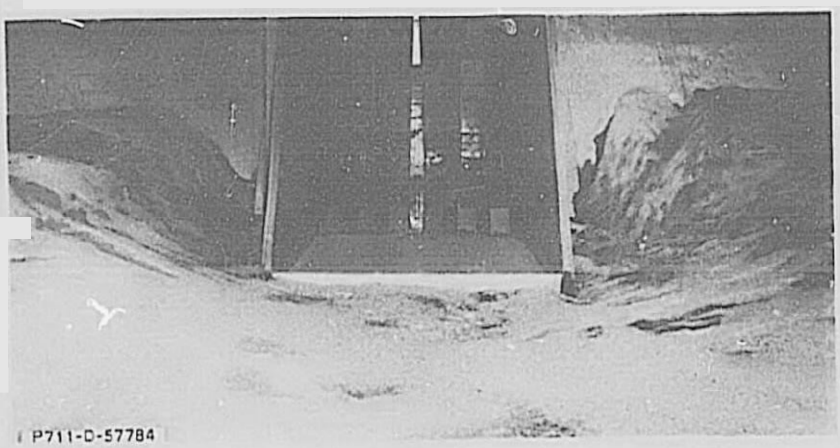
Original Configuration

Figure 18
Report Hyd-573



Right-side view of stilling basin, Q = 4,720 cfs, both valves 100 percent open, reservoir elevation 6101.6, tailwater elevation 5715.5.

Flow conditions in downstream channel.

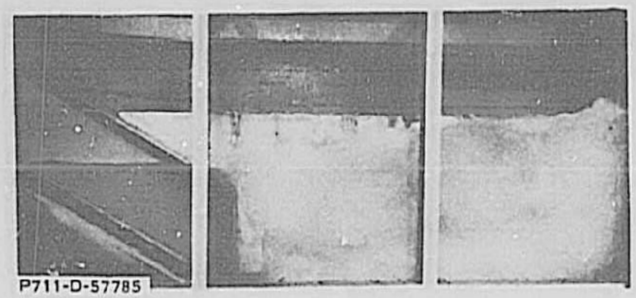


Condition of downstream channel after 4 hours at Q of 4,720 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

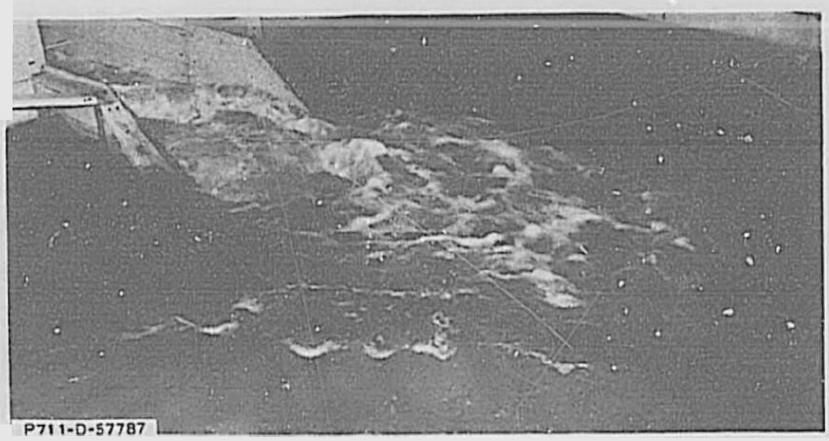
Original Configuration

Figure 19
Report Hyd-573



Right-side view of stilling basin. Q = 2,790 cfs, right valve alone 100 percent open, reservoir elevation 6101.6, tailwater elevation 5714.8.

View from near right valve.

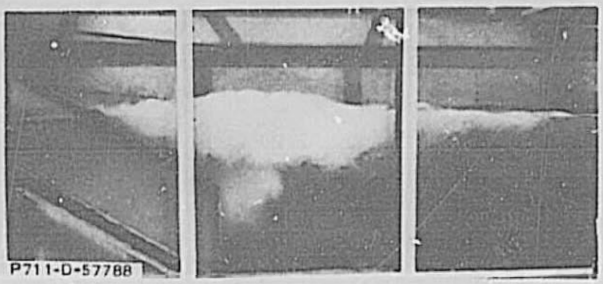


Flow conditions in downstream channel.

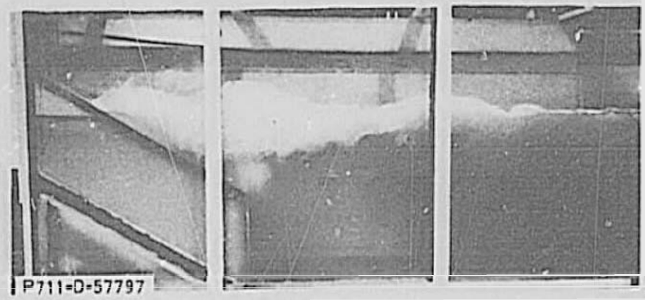
NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Original Configuration

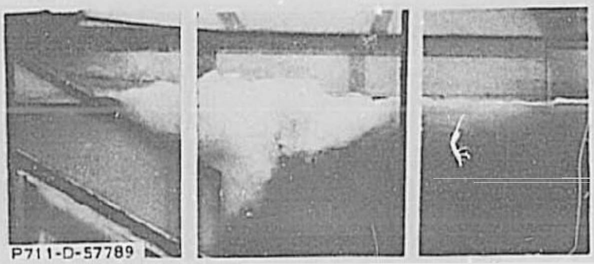
Figure 20
Report Hyd-573



A. Right-side view of stilling basin
Discharge = 1,200 cfs
Both valves open 20-1/2 percent
Reservoir elevation 6000
Tailwater elevation 5714.1

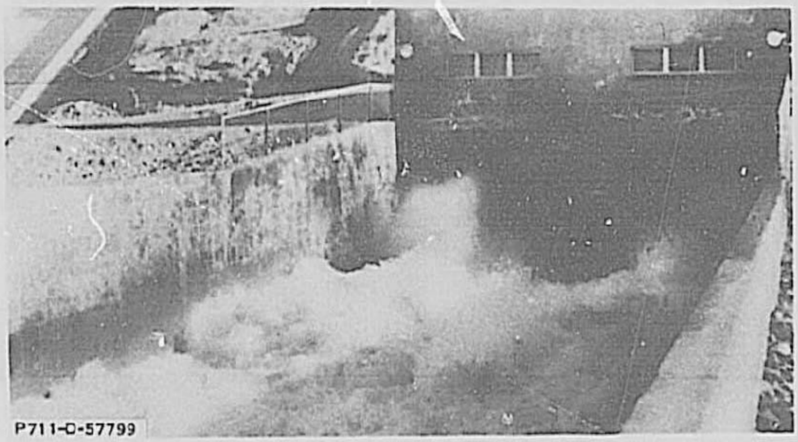


C. Discharge = 1,000 cfs
Both valves open 17 percent
Reservoir elevation 6000
Tailwater elevation 5716.0



B. Discharge = 1,000 cfs
Both valves open 17 percent
Reservoir elevation 6000
Tailwater elevation 5714.0

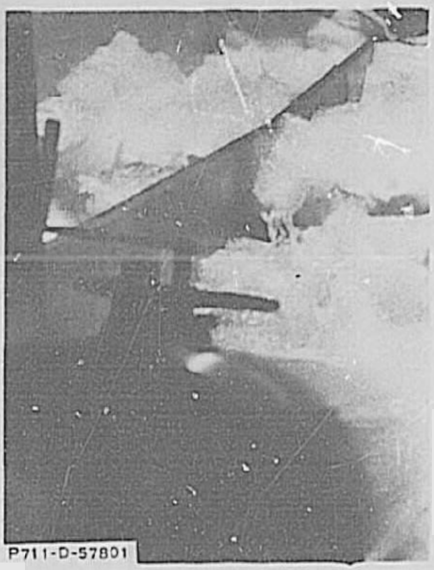
D. Discharge = 1,000 cfs
Both valves open 18-1/2 percent
Reservoir elevation 5960
Tailwater elevation 5716.0



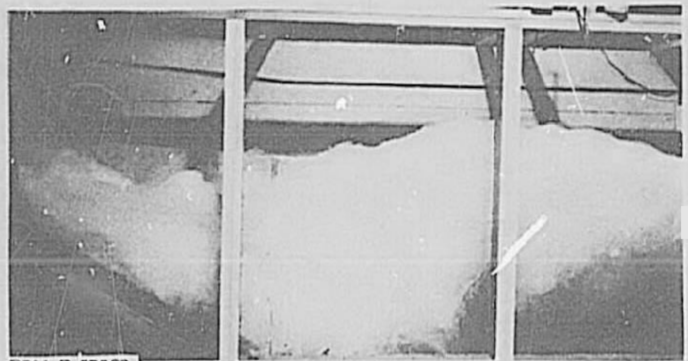
E. Prototype outlet works operating at Q = 1,000 cfs, both valves approximately 17 percent open, reservoir elevation approximately 5989, tailwater elevation approximately 5715.5.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Tests to Determine Maximum Allowable Discharge for Operation with Negligible Jet Penetration and Comparison with Prototype Operation at the Recommended Discharge.

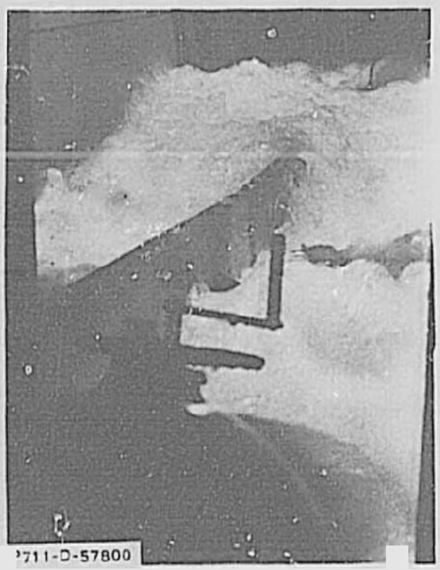

P711-D-57801

View from near right valve,
Q = 1,840 cfs.

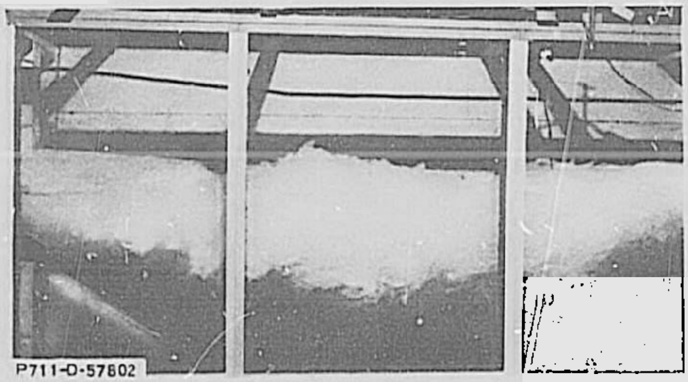

P711-D-57803

Right-side view of stilling basin. Q = 1,840 cfs, both valves 32 percent open, reservoir elevation 5965, tailwater elevation 5714.4.

A


P711-D-57800

View from near right valve,
Q = 3,940 cfs.

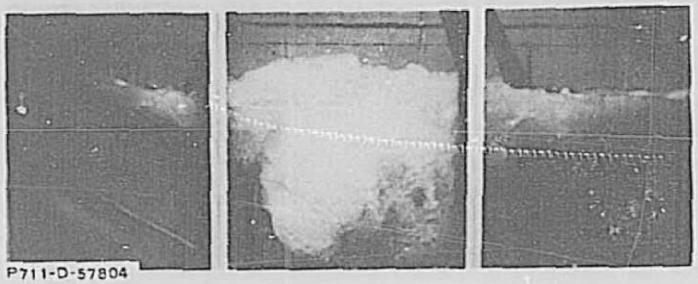

P711-D-57802

Right-side view of stilling basin, Q = 3,940 cfs, both valves 100 percent open, reservoir elevation 6000, tailwater elevation 5715.3. Bottom turbulence is next to center wall and is not visible in this view.

B

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

First Modification, Wedges Removed,
Center Wall Retained


P711-D-57804

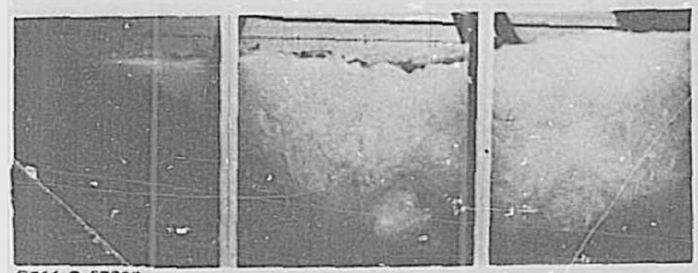
A. Q = 1,840 cfs. Both valves 32 percent open, reservoir elevation 5965, tailwater elevation 5714.4.


P711-D-57806

B. Q = 3,940 cfs. Both valves 100 percent open, reservoir elevation 6000, tailwater elevation 5715.3.


P711-D-57805

C. Q = 4,720 cfs. Both valves 100 percent open, reservoir elevation 6101.6, tailwater elevation 5715.5.


P711-D-57807

D. Q = 4,720 cfs. Both valves 100 percent open, reservoir elevation 6101.6, tailwater elevation 5722.0.


P711-D-57808

E. Q = 2,790 cfs. Left valve alone 100 per cent open, reservoir elevation 6101.6, tailwater elevation 5714.8.

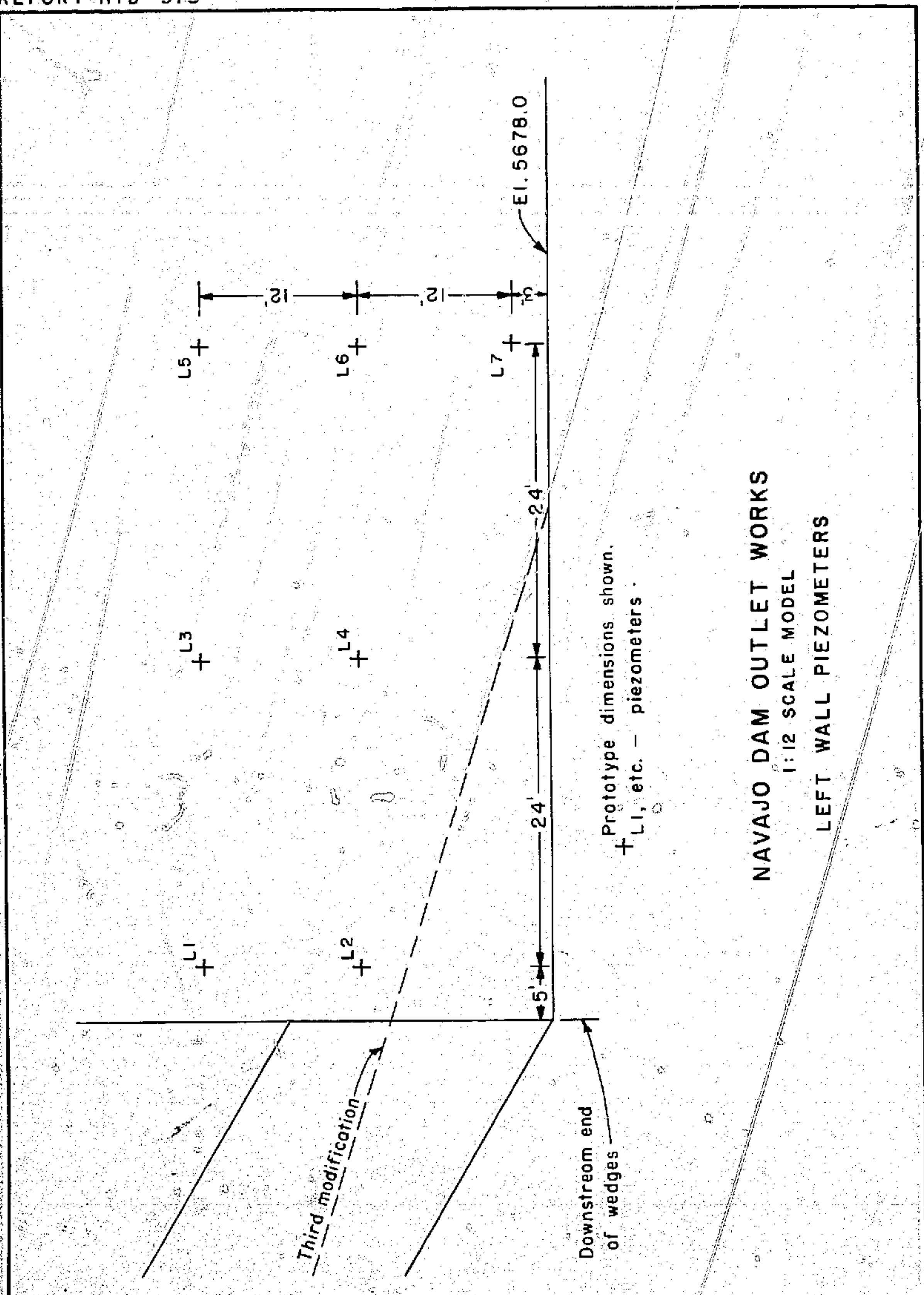

P711-D-57809

F. Q = 2,790 cfs. Left valve alone 100 percent open, reservoir elevation 6101.6, tailwater elevation 5721.5.

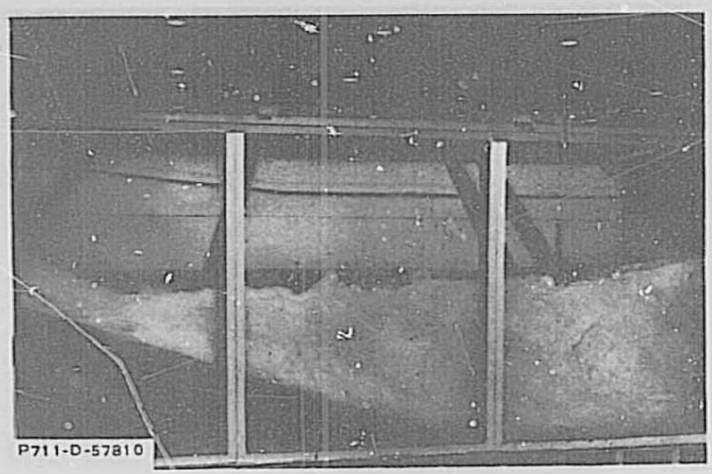
NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Second Modification, Wedges Retained, Center Wall Removed

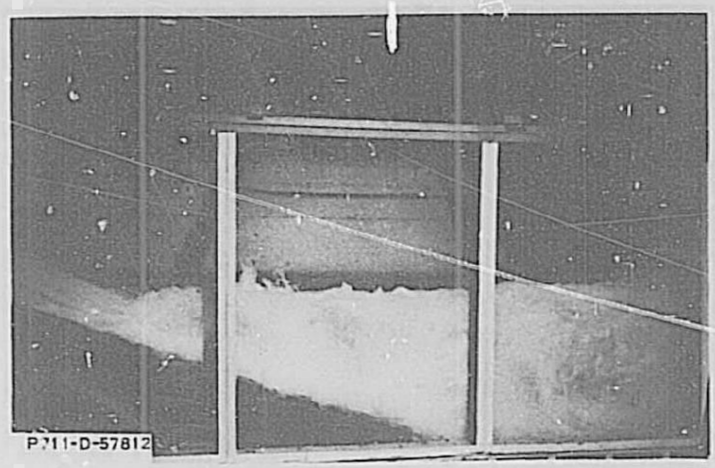
FIGURE 23
REPORT HYD-573



NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL
LEFT WALL PIEZOMETERS



Right-side view of stilling basin. Q = 4,720 cfs, both valves 100 percent open, reservoir elevation 6101.6, tailwater elevation 5715.5.

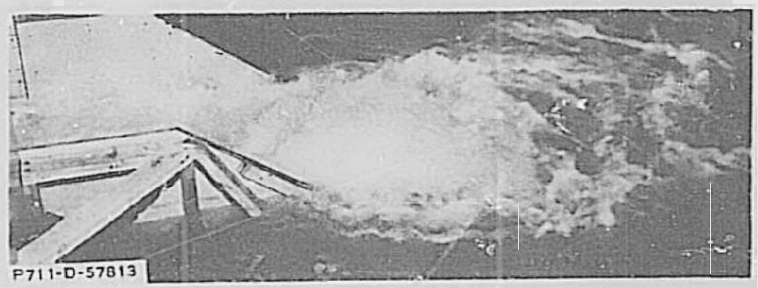


Right-side view of stilling basin, Q = 2,790 cfs, right valve alone 100 percent open, reservoir elevation 6101.6, tailwater elevation 5714.8.

A

B

Flow conditions in downstream channel, Q = 4,720 cfs.

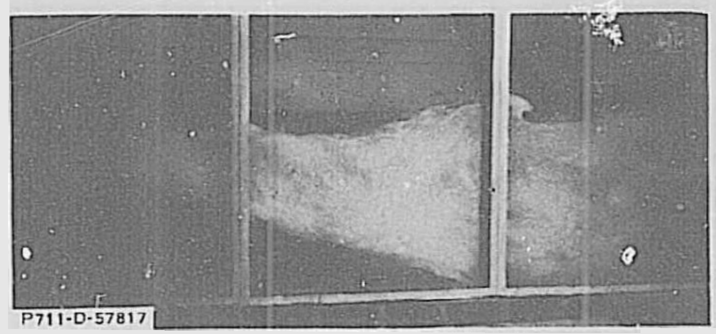


Flow conditions in downstream channel, Q = 2,790 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Third Modification, Wedges and Center Wall Removed, 3:1 Chute Installed

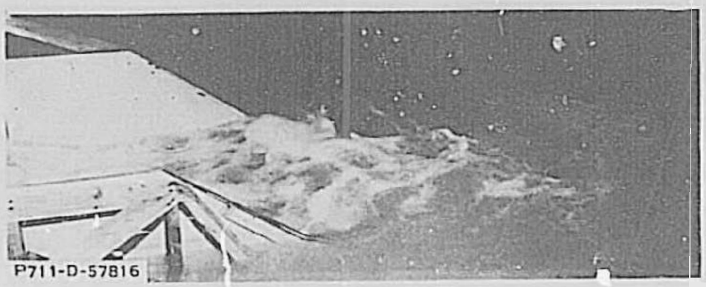
Right-side view of stilling basin. Q = 1,840 cfs, both valves 32 percent open, reservoir elevation 5965, tailwater elevation 5714.4



Right-side view of stilling basin. Q = 3,940 cfs, both valves 100 percent open, reservoir elevation 6000, tailwater elevation 5715.3.

A

B



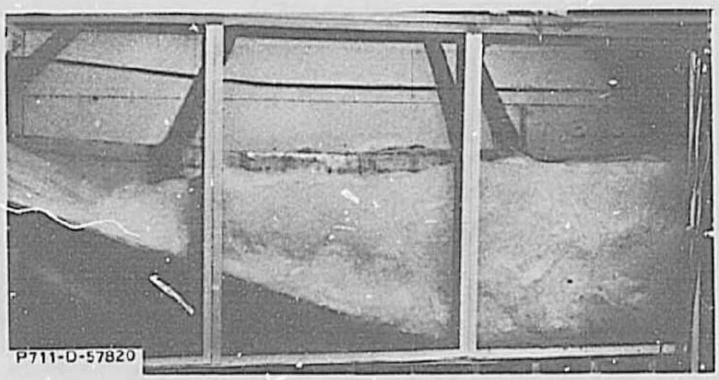
Flow conditions in downstream channel, Q = 1,840 cfs.

Flow conditions in downstream channel, Q = 3,940 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Third Modification, Wedges and Center Wall Removed, 3:1 Chute Installed

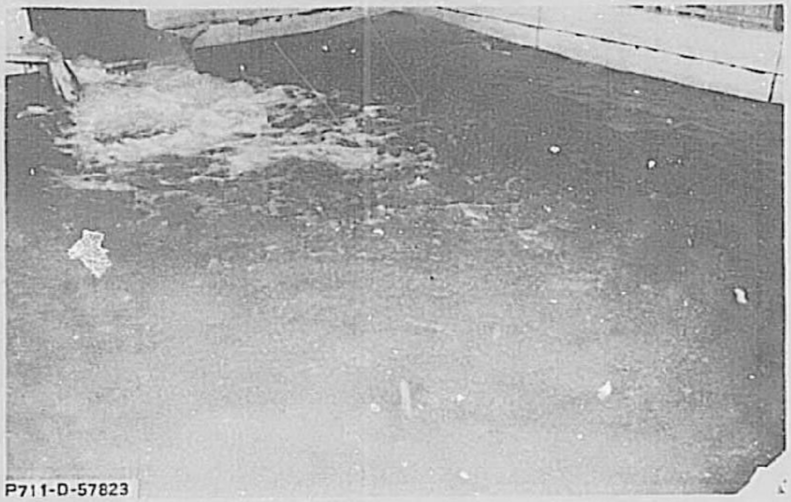
A. Right-side view of stilling basin. Q = 1,840 cfs, both valves 32 percent open, reservoir elevation 5965, tailwater elevation 5714.4.



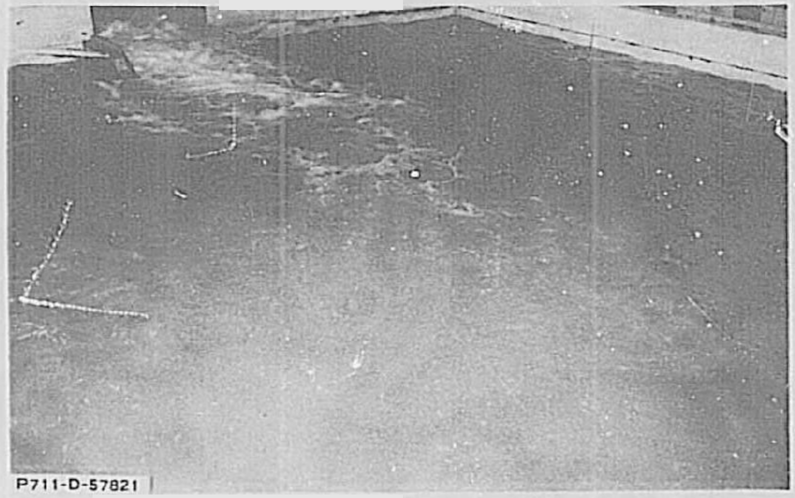
B. Right-side view of stilling basin. Q = 3,940 cfs, both valves 100 percent open, reservoir elevation 6000, tailwater elevation 5715.3.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

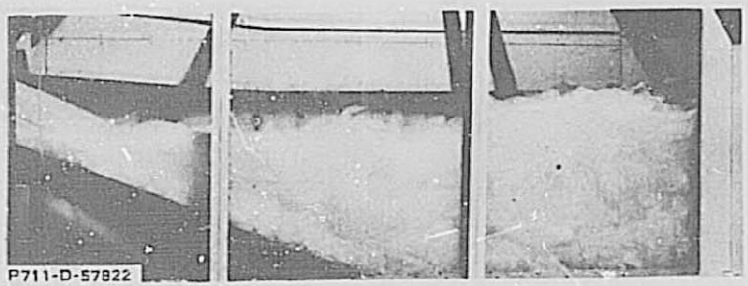
Fourth Modification, 3:1 Chute with Center Wall



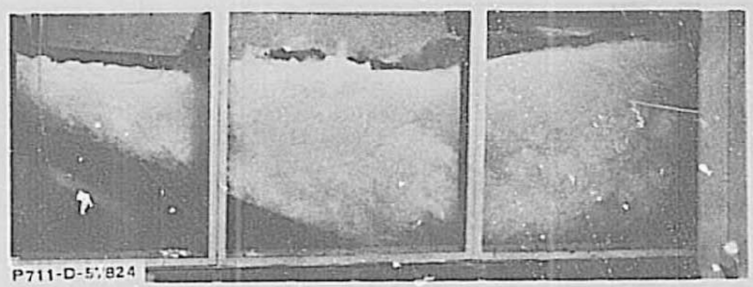
Flow conditions in downstream channel, Q = 4,720 cfs, tailwater elevation 5715.5.



Flow conditions in downstream channel, Q = 4,720 cfs, tailwater elevation 5722.0.



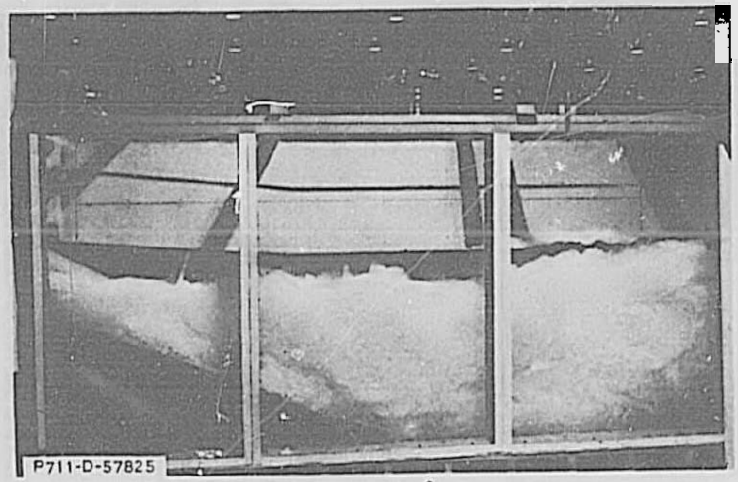
Right-side view of stilling basin. Q = 4,720 cfs, both valves 100 percent open, reservoir elevation 6101.6, tailwater elevation 5715.5.



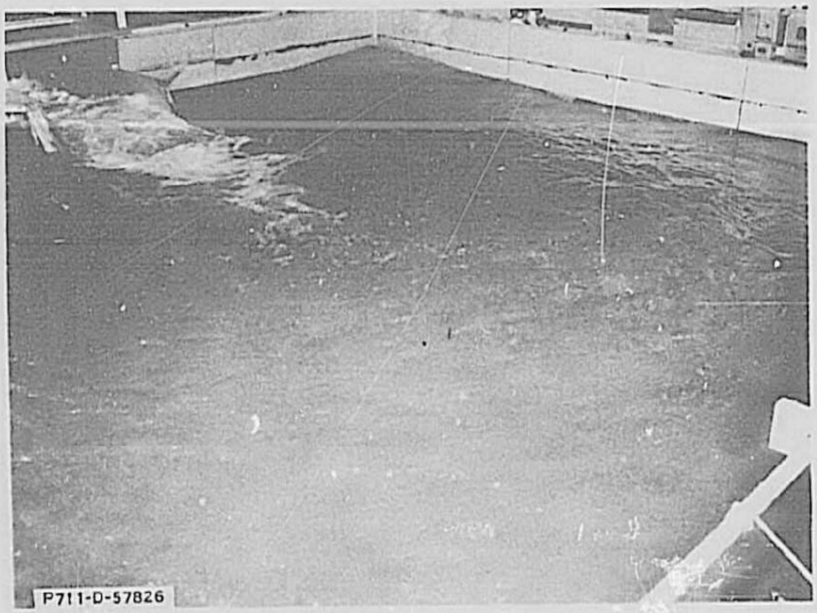
Right-side view of stilling basin. Q = 4,720 cfs, both valves 100 percent open, reservoir elevation 6101.6, tailwater elevation 5722.0

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Fifth Modification, 2-1/2:1 Chute with Extended Center Wall



Right-side view of stilling basin. Q = 3,940 cfs. both valves 100 percent open, reservoir elevation 6000, tailwater elevation 5715.3.

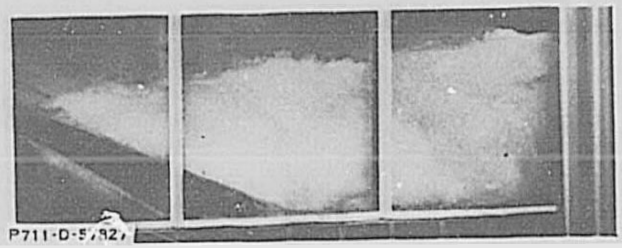


Flow conditions in downstream channel.

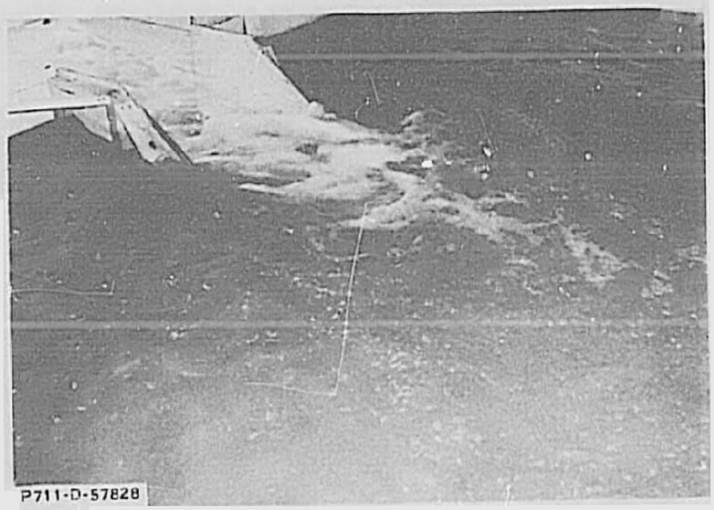
NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Fifth Modification, 2-1/2:1 Chute with Extended Center Wall

Figure 29
Report Hyd-573



Right-side view of stilling basin. Q = 3,200 cfs, both valves 51 percent open, reservoir elevation 6101.6, tailwater elevation 5715.0.

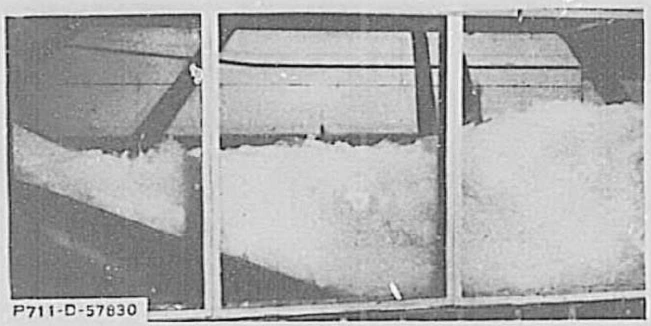


Flow conditions in downstream channel at Q of 3,200 cfs.

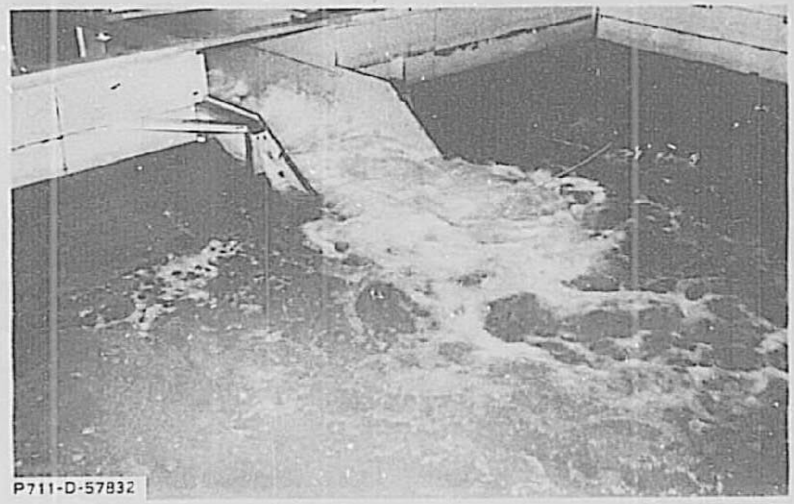
Condition of downstream channel after 4 hours at Q of 3,200 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

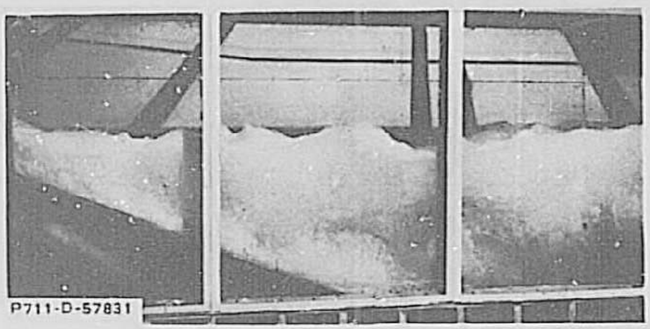
Sixth Modification, 2-1/2:1 Chute without Center Wall



Right-side view of stilling basin with right jet along outside wall. Q = 3,200 cfs, both valves 51 percent open, reservoir elevation 6101.6, tailwater elevation 5715.0.



Flow conditions in downstream channel, Q = 3,200 cfs.



Right-side view of stilling basin with right jet moving away from outside wall, Q = 3,200 cfs

Condition of downstream channel after 4 hours at Q of 3,200 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Seventh Modification, 2-1/2:1 Chute Without Center Wall, Valves Tipped 3°.

FIGURE 31
REPORT HYD. 573

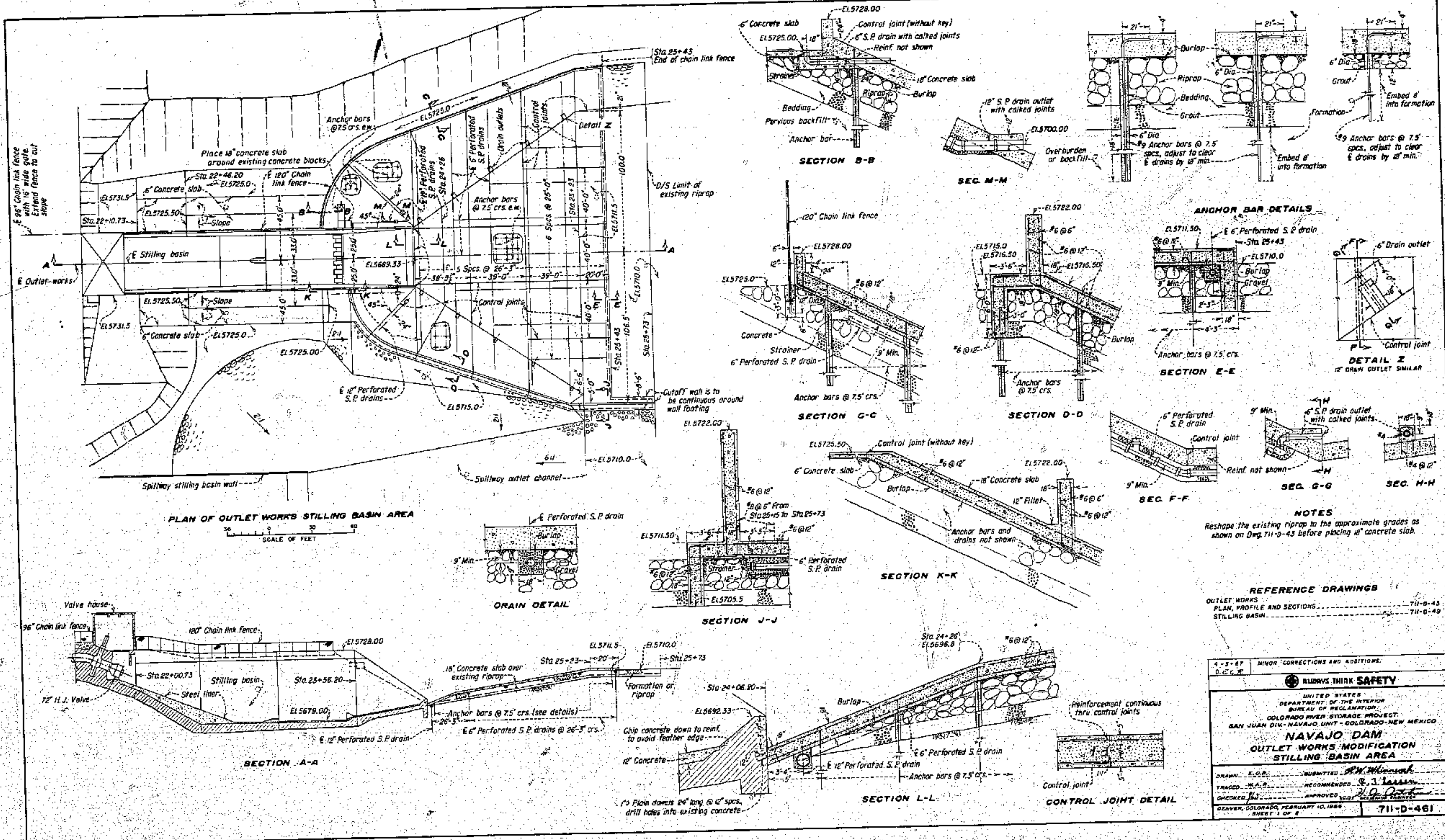
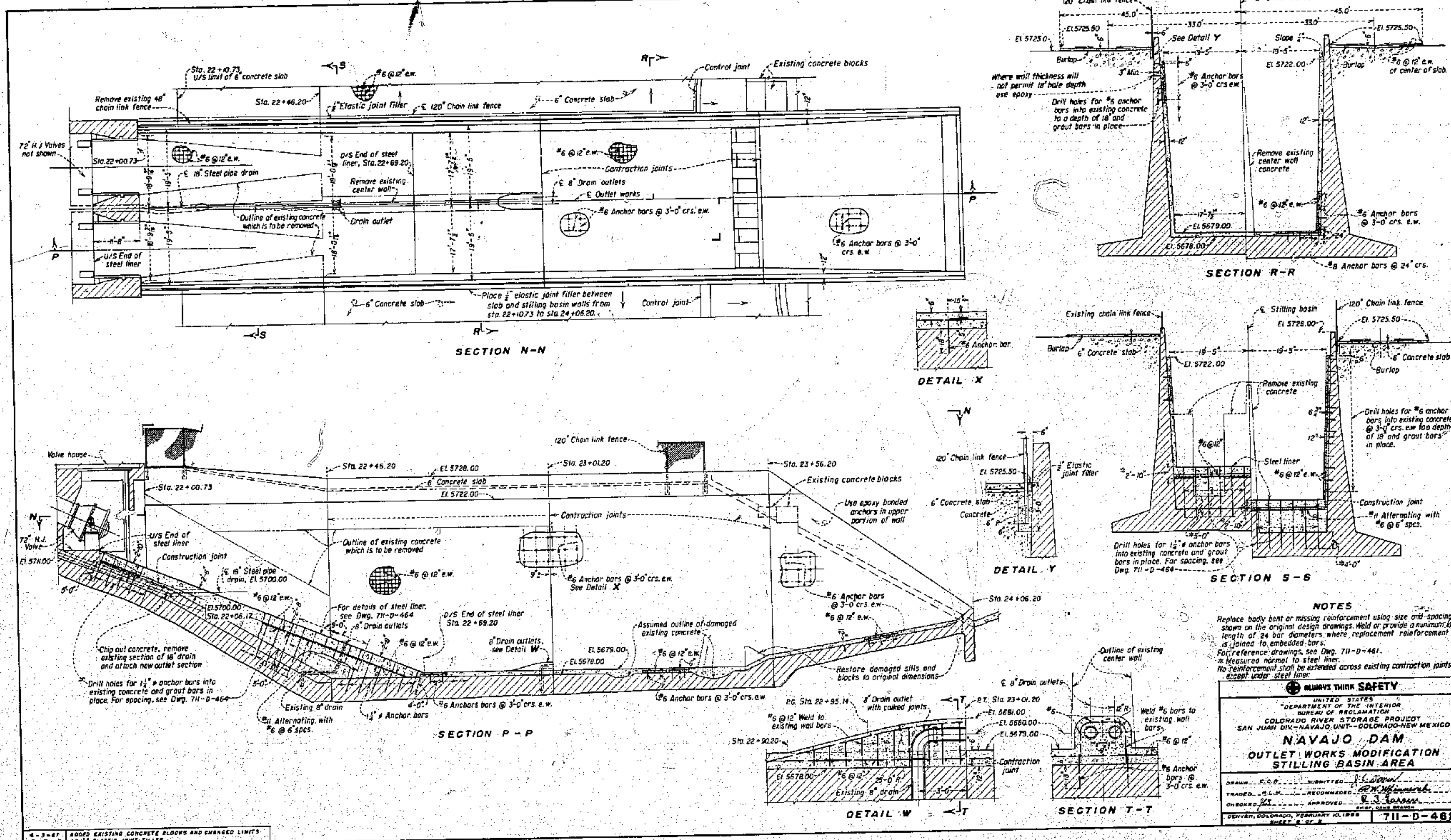
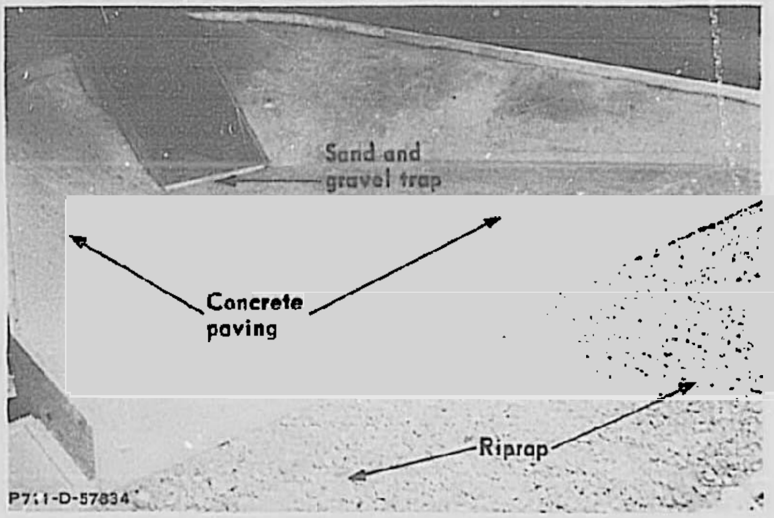
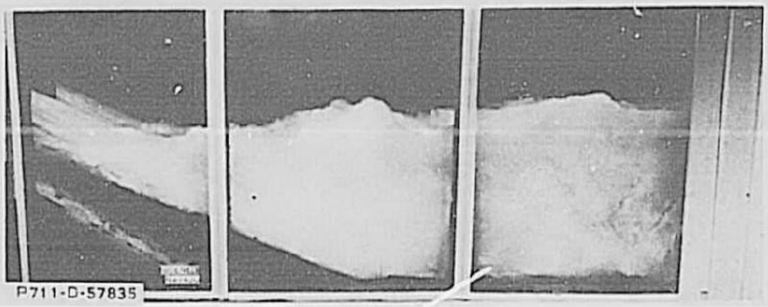


FIGURE 32
REPORT HYD. 573





Recommended configuration of downstream channel.



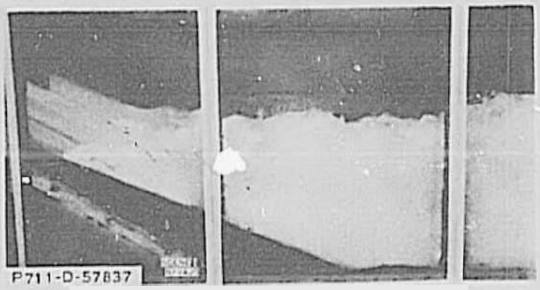
Right-side view of stilling basin. Q = 3,200 cfs, both valves 52 percent open, reservoir elevation 6085, tailwater elevation 5715.0.

Flow conditions in downstream channel, Q = 3,200 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

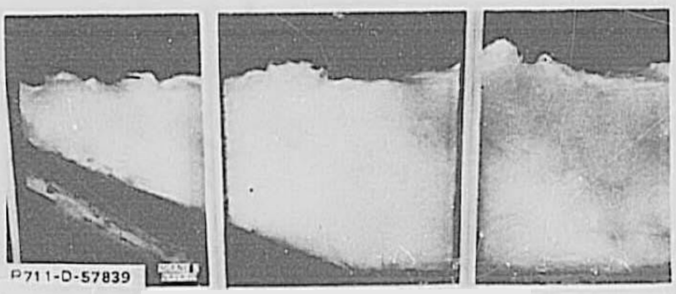
Recommended Design

Figure 34
Report Hyd-573



Right-side view of stilling basin.

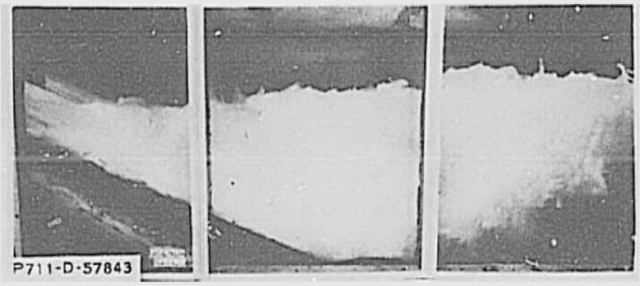
Flow conditions in downstream channel. Q = 4, 720 cfs, both valves 100 percent open, reservoir elevation 6101. 6, tailwater elevation 5715. 5.



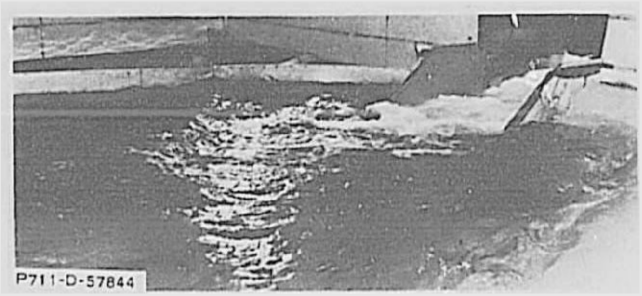
Right-side view of stilling basin.

Flow conditions in downstream channel. Q = 4, 720 cfs, both valves 100 percent open, reservoir elevation 6101. 6, tailwater elevation 5722. 0.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model
Recommended Design

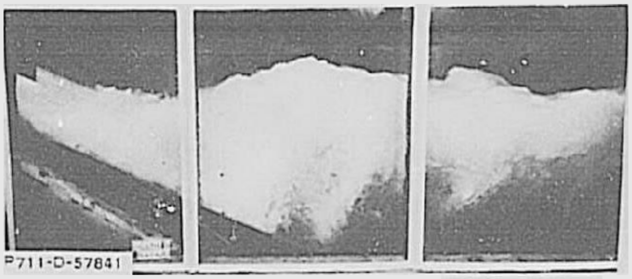


Right-side view of stilling basin.



A

Flow conditions in downstream channel. Q = 2,500 cfs, both valves 30 percent open, reservoir elevation 6085, tailwater elevation 5714.6.



Right-side view of stilling basin

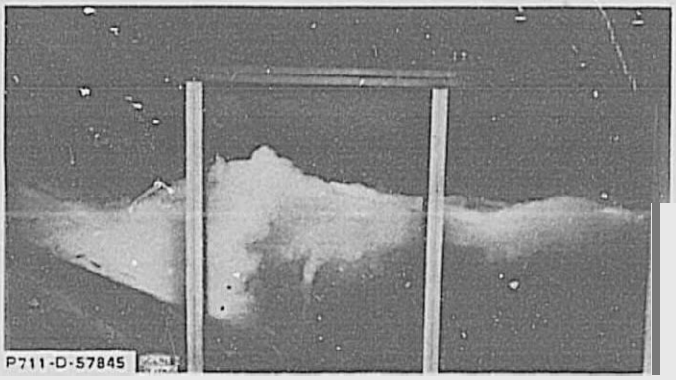
B

Flow conditions in downstream channel. Q = 2,000 cfs, both valves 30 percent open, reservoir elevation 6085, tailwater elevation 5714.4.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Recommended Design

Figure 36
Report Hyd-573

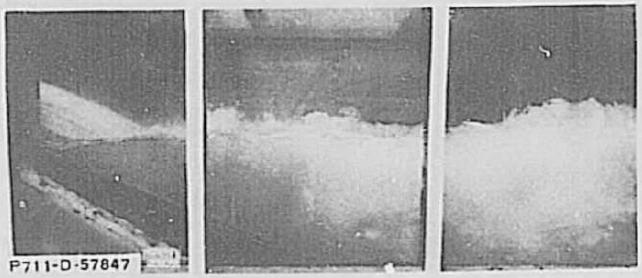


Right-side view of stilling basin. Q = 1,500 cfs, both valves 22 percent open, reservoir elevation 6085, tailwater elevation 5714.3.

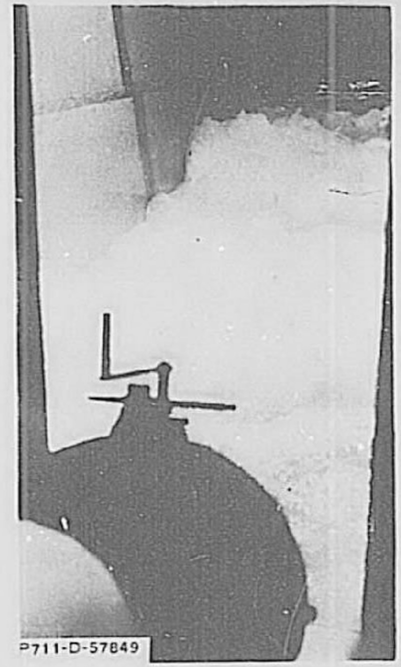
Flow conditions in downstream channel, Q = 1,500 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

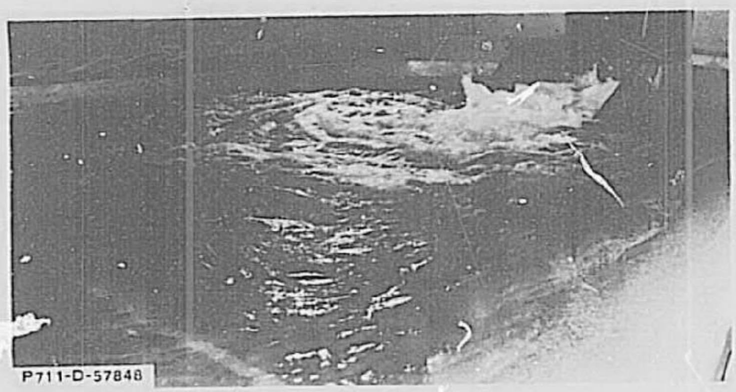
Recommended Design



Right-side view of stilling basin. Q = 2,790 cfs, left valve alone 100 percent open, reservoir elevation 6101.6, tailwater elevation 5714.8.



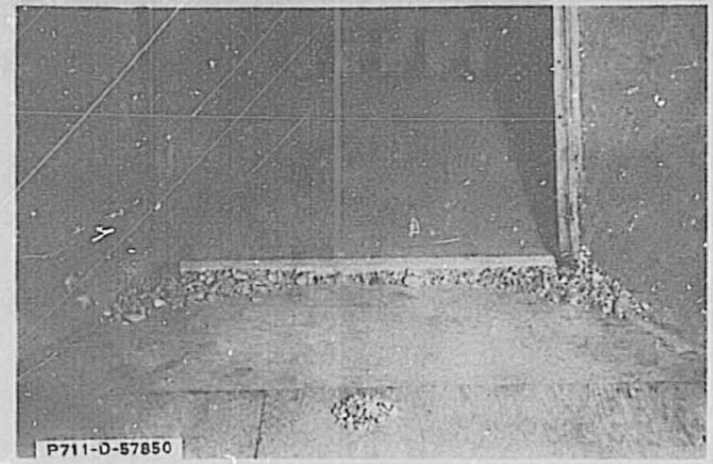
View from near right valve, Q = 2,790 cfs.



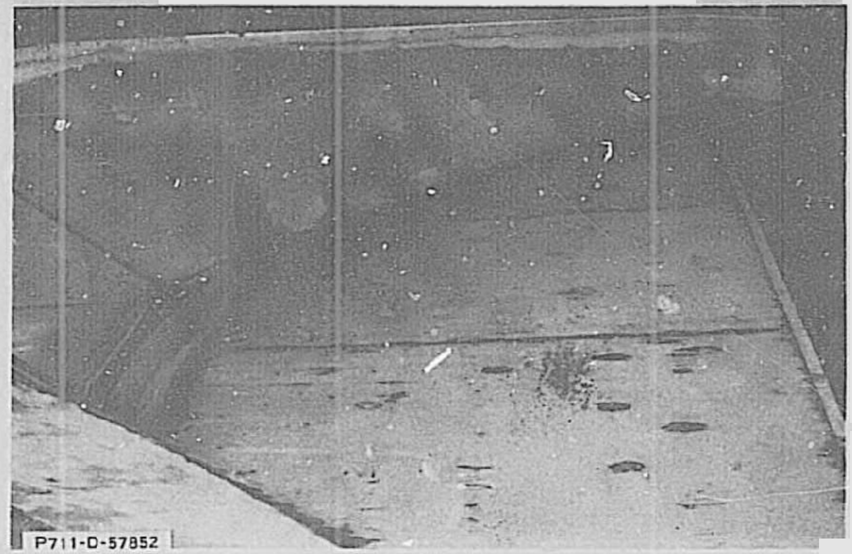
Flow conditions in downstream channel. Q = 2,790 cfs.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

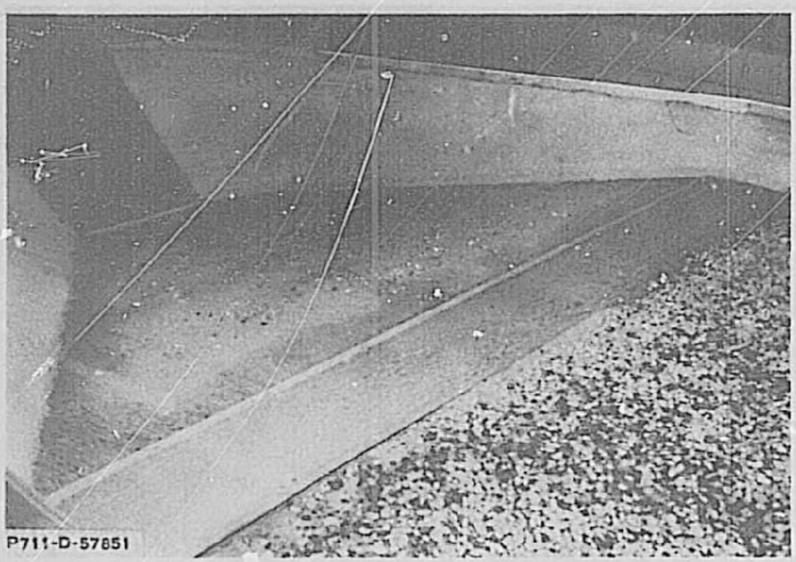
Recommended Design



A. Preliminary 18-inch-deep rock trap. Photograph shows material caught in trap and material which entered basin during operation at Q of 3, 200 cfs.



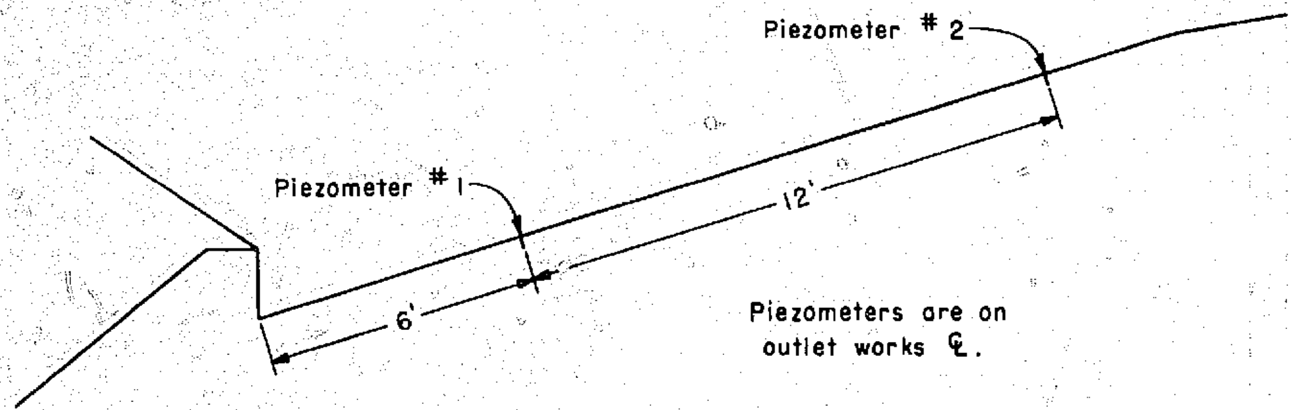
C. Material location after operation at Q of 3, 200 cfs with 36-inch rock trap. No material was found in the basin.



B. Location of material on paving before test with 36-inch-deep rock trap.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

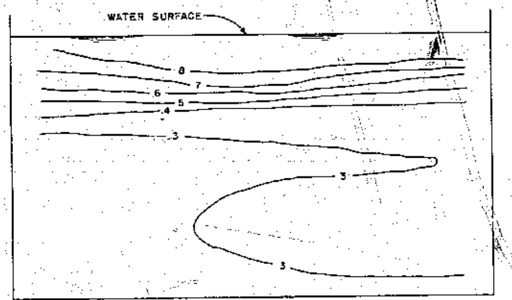
Recommended Design



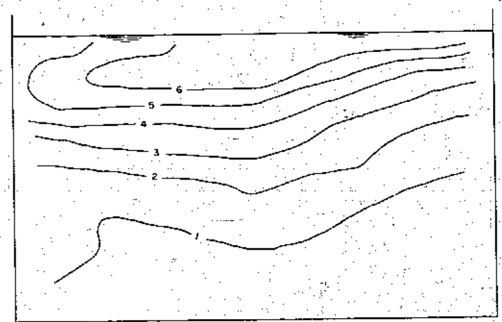
	MAXIMUM FLUCTUATION, FT. OF WATER (PROTOTYPE)		
	Q = 3200 CFS Res. El. 6101.6 TW El. 5715.0	Q = 4720 CFS Res. El. 6101.6 TW El. 5715.5	Q = 4720 CFS Res. El. 6101.6 TW El. 5722.0
Piezometer # 1	0.0	0.5	0.5
Piezometer # 2	2.5	3.5	2.5

NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL
PRESSURE FLUCTUATION ON THE CONCRETE PAVING
IMMEDIATELY DOWNSTREAM FROM THE STILLING BASIN
RECOMMENDED DESIGN

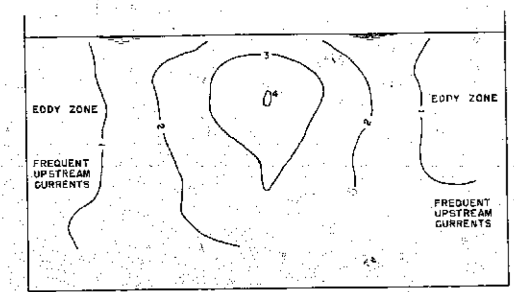
721



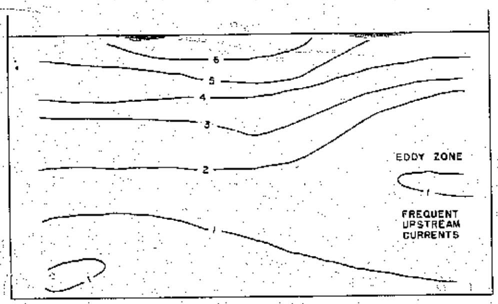
Q = 4720 cfs
RES. EL. 6101.6
TAILWATER EL. 5715.5



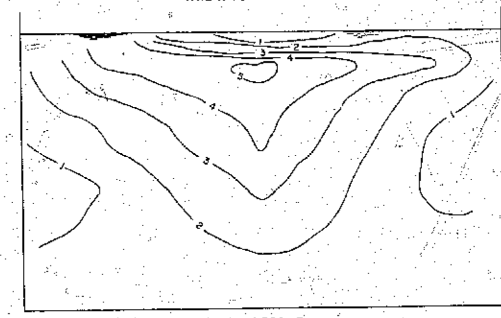
Q = 3200 cfs
RES. EL. 6085.0
TAILWATER EL. 5715.0



Q = 1500 cfs
RES. EL. 6085.0
TAILWATER EL. 5714.3

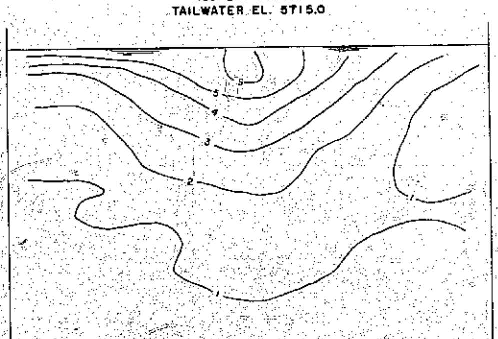


Q = 3200 cfs
RES. EL. 6101.6
TAILWATER EL. 5715.0



Q = 2500 cfs
RES. EL. 6085.0
TAILWATER EL. 5714.6

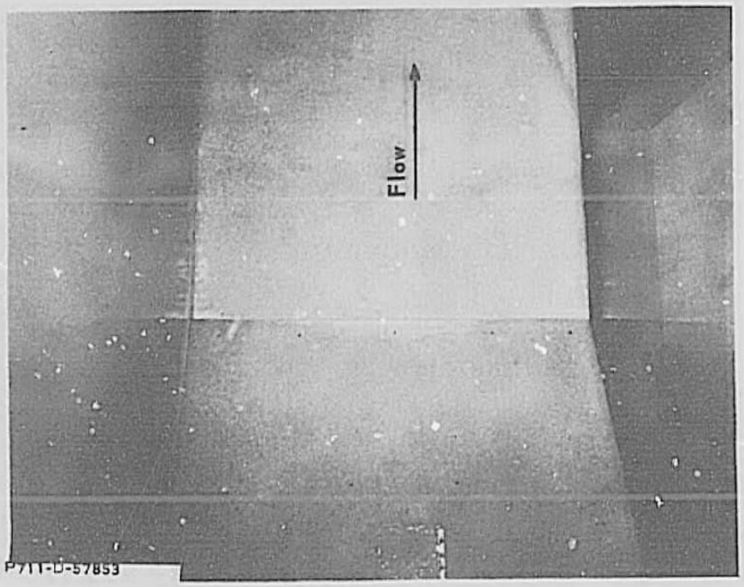
Velocities have units of feet per second (prototype).
Station 24+00, looking downstream.



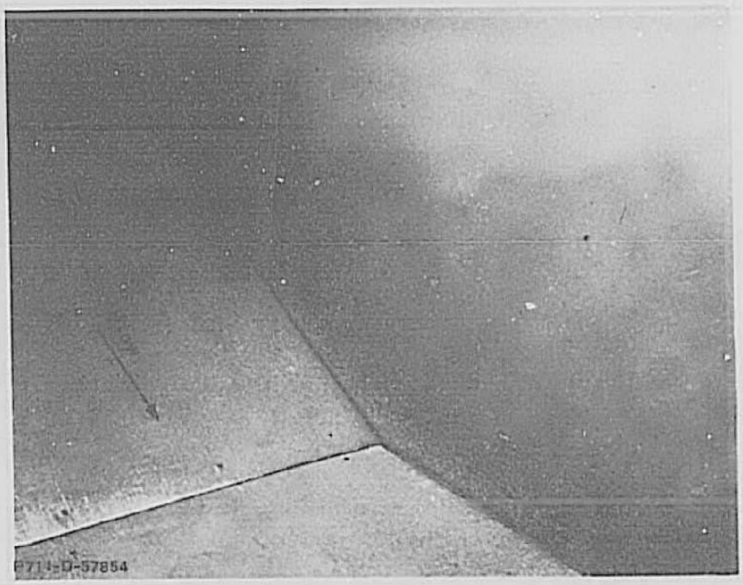
Q = 3200 cfs
RES. EL. 6101.6
TAILWATER EL. 5721.8

Q = 2000 cfs
RES. EL. 6085.0
TAILWATER EL. 5714.4

NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL
VELOCITY CONTOURS AT DOWNSTREAM END OF STILLING BASIN
(STATION 24+00)



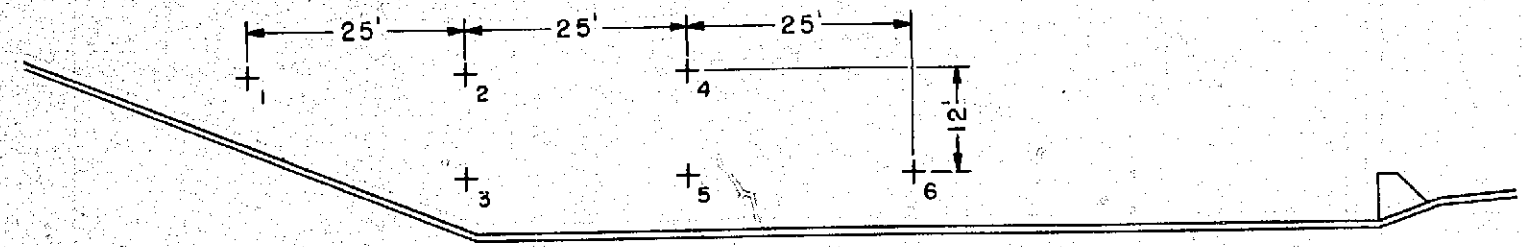
Chute and stilling basin floor abrasion after 5-1/2 hours at Q = 2,500 cfs, reservoir elevation 6085.



Floor and wall abrasion after 5-1/2 hours at Q = 2,500 cfs, reservoir elevation 6085.

NAVAJO DAM OUTLET WORKS
1:12 Scale Model

Recommended Design

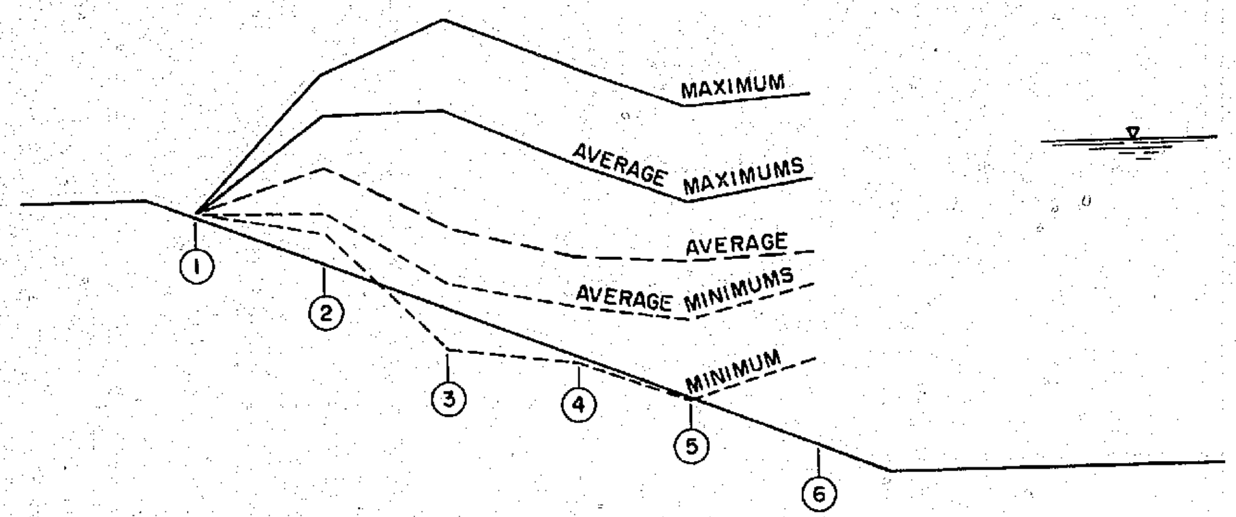


Prototype dimensions shown.
+1, etc. - piezometers

NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL
LEFT WALL PIEZOMETERS - RECOMMENDED DESIGN

721

721



PIEZ. NO.	FREQUENCY OF FLUCTUATION CYCLES PER SECOND (PROTOTYPE)
1	NO FLUCTUATION
2	≈10.0
3	4.8
4	3.0
5	1.2
6	1.3

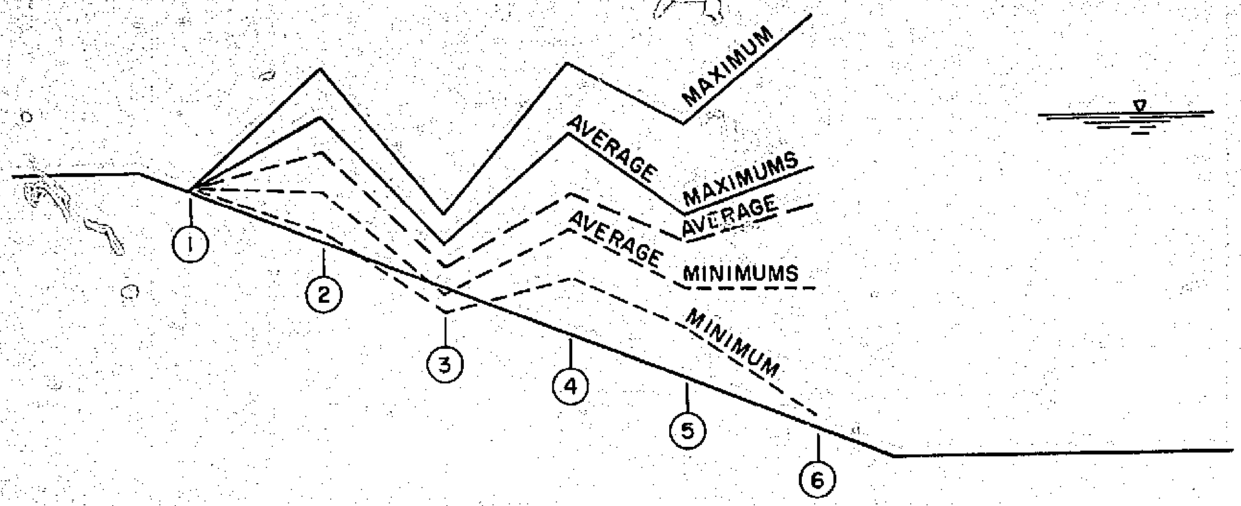
LINEAR SCALE AND PRESSURE SCALE: 1" = 20'

1 etc. - piezometer locations

Q = 3200 CFS
Res. El. 6101.6
TW El. 5715.0

NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL

INSTANTANEOUS PRESSURES ON THE CHUTE
FOR THE RECOMMENDED DESIGN



PIEZ. NO.	FREQUENCY OF FLUCTUATION CYCLES PER SECOND (PROTOTYPE)
1	NO FLUCTUATION
2	∿20.0
3	10.1
4	2.3
5	1.6
6	1.9

LINEAR SCALE AND PRESSURE SCALE: 1" = 20'

(1) etc. – piezometer locations

Q = 4720 CFS
Res. El. 6101.6
TW El. 5715.5

NAVAJO DAM OUTLET WORKS
1:12 SCALE MODEL

INSTANTANEOUS PRESSURES ON THE CHUTE
FOR THE RECOMMENDED DESIGN

721

7-1750
(2-67)
Bureau of Reclamation

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
	MASS	
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
	FORCE/AREA	
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
	MASS/VOLUME (DENSITY)	
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
	MASS/CAPACITY	
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
	BENDING MOMENT OR TORQUE	
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^{6}	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^{7}	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
	VELOCITY	
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
	ACCELERATION*	
Feet per second^2	0.3048*	Meters per second^2
	FLOW	
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
	FORCE*	
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes

Multiply	By	To obtain
	WORK AND ENERGY*	
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
	POWER	
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
	HEAT TRANSFER	
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
	WATER VAPOR TRANSMISSION	
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

GPO 835-159

ABSTRACT

Damage which occurred to the hollow-jet valve outlet works stilling basin at the Navajo Dam was duplicated in a 1:12 scale model. Severe abrasion damage in the upstream portion of the prototype basin probably occurred during several months' operation at approximately 30% valve opening under 245 ft of head. Abrasion in the downstream end probably occurred during operation with 100% valve opening and about 280 ft of head. Model tests indicated the original hollow-jet valve basin, with converging wedges and a center dividing wall, could not be improved in efficiency of energy dissipation and stability. This design, however, permitted the development of areas of intense turbulence, with accompanying circulation of abrasive materials. Also, the center wall was subjected to fluctuating pressures which could result in structural damage due to vibration. The basin was modified by eliminating the center wall and wedges, reducing the allowable maximum discharge, and paving part of the downstream channel. The paving is necessary to prevent streambed material from entering the modified stilling basin. Tests on the original configuration under various operating conditions, on 7 proposed modifications, and on the recommended design are described. An appendix reviews damages reported in other similar stilling basins.

ABSTRACT

Damage which occurred to the hollow-jet valve outlet works stilling basin at the Navajo Dam was duplicated in a 1:12 scale model. Severe abrasion damage in the upstream portion of the prototype basin probably occurred during several months' operation at approximately 30% valve opening under 245 ft of head. Abrasion in the downstream end probably occurred during operation with 100% valve opening and about 280 ft of head. Model tests indicated the original hollow-jet valve basin, with converging wedges and a center dividing wall, could not be improved in efficiency of energy dissipation and stability. This design, however, permitted the development of areas of intense turbulence, with accompanying circulation of abrasive materials. Also, the center wall was subjected to fluctuating pressures which could result in structural damage due to vibration. The basin was modified by eliminating the center wall and wedges, reducing the allowable maximum discharge, and paving part of the downstream channel. The paving is necessary to prevent streambed material from entering the modified stilling basin. Tests on the original configuration under various operating conditions, on 7 proposed modifications, and on the recommended design are described. An appendix reviews damages reported in other similar stilling basins.

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Hyd-573
King, D L
HYDRAULIC MODEL STUDIES OF THE MODIFIED OUTLET WORKS STILLING BASIN--NAVAJO DAM, COLORADO RIVER STORAGE PROJECT, NEW MEXICO. USBR Lab Rept Hyd-573, Hyd Br, June 1967. Bureau of Reclamation, Denver, 26 p, 44 fig, 9 tab, 4 ref, append

DESCRIPTORS-- research and development/ *outlet works/ *model tests/ water pressures/ hydraulic models/ piezometers/ pressure measuring equip/ energy dissipation/ riprap/ velocity distribution/ hydraulic jumps/ hydraulics/ hydraulic structures/ erosion/ high pressure valves/ hollow jet valves/ *stilling basins/ rigid linings/ wave action/ vortices/ *damages/ abrasion/ scour/ concrete structures
IDENTIFIERS-- Navajo Dam, N Mex/ New Mexico/ Colorado River Storage Proj/ design modifications

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